A VALUE-FOCUSED THINKING MODEL FOR THE SELECTION OF THE BEST RIGID PAVEMENT PARTIAL-DEPTH SPALL REPAIR MATERIAL

THESIS

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AFIT/GEM/ENS/07-04

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Abstract

Concrete spalls on airfield pavements generate foreign object debris (FOD) that is damaging to aircraft engines, and may damage landing gear by roughening the pavement surface. Repairing spalled concrete on aging and deteriorating airfields is essential for its safe operational use. Picking the best repair material from many products on the commercial market is difficult. There is wide variation on material properties, and good performance on certain criteria is critical to constructing long lasting repairs.

Since there is currently no procedure for Air Force decision-makers to select the best rigid-pavement repair material, a model was created using Value-Focused Thinking (VFT) to evaluate repair material alternatives. Fourteen products were compared against each other. Each was scored using fourteen evaluation measures that were identified as important to the repair material selection process. Pavemend EX-H was found to be the best choice for repairs conducted during conventional, steady-state operations. Pavemend VR was found to be the best option for repairs that must be ready for traffic within hours after placement, such as during contingency operations. VFT was shown to be an effective methodology for objectively ranking repair products, while providing a systematic process that can be tailored for future circumstances.

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Table of Contents

Page

Abstract iv

Acknowledgments v

List of Figures viii

List of Tables xi

I. Introduction 1

1.1 Overview 1
1.2 Background 3
1.3 Problem Identification 3
1.4 Research Questions 4
1.5 Research Approach 5
1.6 Scope 6
1.7 Significance 6
1.8 Summary 7

II. Literature Review 8

2.1 Overview 8
2.2 Decision Analysis Approaches 8
2.2.1 Analytical Hierarchy Process (AHP) 8
2.2.2 Life Cycle Cost Analysis (LCCA) 9
2.2.3 Expert Systems 10
2.3 Property Testing and Field Performance of repair materials 13
2.3.1 Material Properties 15
2.3.1.1 Compatibility 15
2.3.2 Other Properties of Concern 18
2.4 Decision Analysis 20
2.4.1 Value-Focused Thinking 22

III. Methodology 26

3.1 Overview 26
3.2 Problem Identification 26
3.3 Constructing the Value Hierarchy 27
3.3.1 Cost 30
3.3.2 Desirable Material Properties 31
3.3.3 Shelf Life 33
3.3.4 Site Preparation Required 34

Page

3.3.5 Workability 34
3.3.6 Complete Hierarchy 35
3.4 Develop Evaluation Measures 37
3.4.1 Cost 38
3.4.2 Desired Material Properties 38
3.4.3 Shelf Life 39
3.4.4 Site Preparation Required 39
3.4.5 Workability 40
3.5 Weighting the Hierarchy 40
3.6 Creating Value Functions 42
3.6.1 Cost Value Functions 44
3.6.2 Desirable Material Properties Value Functions 45
3.6.3 Shelf Life Value Function 51
3.6.4 Site Preparation Required Value Function 52
3.6.5 Workability Value Functions 53
3.7 Alternative Generation 54

IV. Results and Analysis 56

4.1 Overview 56
4.2 Alternative Scoring 56
4.3 Deterministic Analysis (Conventional Weighting) 58
4.3.1 Deterministic Analysis on a Conventionally Weighted Scenario 58
4.3.2 Contingency Weighting Deterministic Analysis 61
4.4 Sensitivity Analysis 63
4.4.1 Sensitivity on Fundamental Objectives 64
4.5 Summary of Results and Analysis 68

V. Summary and Conclusions 72

5.1 Overview 72
5.2 Research Summary 72
5.3 Model Strengths 74
5.4 Model Limitations 75
5.5 Future Research 75
5.6 Conclusions 76

Appendix A: Sensitivity Graphs on Measures (Conventional Weighting) 77

Appendix B: Sensitivity Graphs on Measures (Contingency Weighting) 84

Bibliography 91

Vita 93

List of Figures

Page

Figure 1. Concrete Pavement Spalls....2
Figure 2. Example of a Failed Concrete Pavement Repair 7
Figure 3. Variable Inputs on SCEPTRE 1.1 Program....11
Figure 4. SCEPTRE 1.1 Expected Pavement Service Life Output....12
Figure 5. Factors Affecting Durability of a Concrete Repair System 14
Figure 6. Properties that Affect Compatibility between Repair Material and Substrate..
....15
Figure 7. VFT Ten-Step Process 22
Figure 8. Hierarchy Tiers 23
Figure 9. Example Piecewise Linear Function....24
Figure 10. Example Exponential 24
Figure 11. Advantages to using VFT 27
Figure 12. First Tier Hierarchy Values 29
Figure 13. Cost Branch....31
Figure 14. Desirable Material Properties Branch....32
Figure 15. Shelf Life Branch....34
Figure 16. Site Preparation Required Branch....34
Figure 17. Workability Branch....35
Figure 18. Complete Hierarchy 37
Figure 19. Cost per Yield SDVF 44

Page

Figure 20. Requires Specialized Aggregates....45

Figure 21. ASTM C 882 SDVF....46

Figure 22. ASTM C 39 SDVF....46

Figure 23. ASTM C 666 SDVF....47

Figure 24. SDVF for Early Strength (ASTM C 39 after 3 hours of curing)....48

Figure 25. Modulus of Elasticity Differential from Substrate SDVF....49

Figure 26. Restrained Shrinkage SDVF....50

Figure 27. Thermal Coefficient SDVF (deviation from 5 microstrains/°F)....51

Figure 28. Shelf Life SDVF....51

Figure 29. SDVF for Bonding Agent Requirement....52

Figure 30. SDVF for Material Hydrophobicity....53

Figure 31. SDVF for Aggregate/Lift Requirement....53

Figure 32. SDVF for Initial Set Time (deviation from 45 minutes)....54

Figure 33. Alternative Rankings under Conventional Weighting....58

Figure 34. Alternative Rankings with Respect to Fundamental Objectives (Conventional Weighting)....59

Figure 35. Alternative Rankings with Respect to Evaluation Measures (Conventional Weighting)....60

Figure 36. Ranking of Alternatives using Contingency Weighting....61

Figure 37. Alternative Ranking with Respect to Fundamental Objectives (Contingency Weighting)....62

Figure 38. Alternative Ranking with Respect to Evaluation Measures (Contingency Weighting) 63

Figure 39. Sensitivity Analysis on Cost Value.....65

Figure 40. Sensitivity Analysis on Desirable Material Properties Value.....65

Figure 41. Sensitivity Analysis on Shelf Life Value.....66

Figure 42. Sensitivity Analysis on Site-Preparation Required Value 67

Figure 43. Senstivity Analysis on Workability Value.....67

List of Tables

Page

Table 1. Definitions of First Tier Values 30

Table 2. Desired Material Properties Values 33

Table 3. Desired Material Properties Measures 39

Table 4. Weight Assignments for Conventional Spall Repair 41

Table 5. Weight Assignments for Contingency Spall Repair 42

Table 6. Repair Materials Scored in Model 55

Table 7. Summary Matrix of Alternative Scores 57

Table 8. Summary of Weight Sensitivity on Values 69-71

Table 9. Summary of Research Questions 72

A VALUE-FOCUSED THINKING MODEL FOR THE SELECTION OF THE BEST RIGID PAVEMENT, PARTIAL-DEPTH SPALL REPAIR MATERIAL

I. Introduction

1.1 Overview

Portland Cement Concrete (PCC) is the most common pavement surface used in airfield runways, taxiways and parking aprons. When properly designed, constructed, and maintained, it provides a smooth surface capable of supporting the loads and tire pressures of all types of aircraft. However, PCC pavements that have outlived their useful lives or that have not been maintained may develop cracks and spalls that are damaging to the pavement surface. A spall is a pavement distress in the form of a crack, often along pavement joints and edges. Figure 1 shows typical spalls in concrete pavement. Spalls are commonly partial depth, but may be full depth, in which case the structural capacity of the slab is weakened. Repairing spalls as they occur is important for maintaining the health of airfield pavements, and is essential to the safety of aircraft as they take off, land, and taxi. Engineers from all branches of service perform these repairs, to include Air Force Civil Engineers, Navy Seabees, and Army Combat Engineers.

Figure 1. Concrete Pavement Spalls

Military engineers need a decision tool to identify which repair materials are ideal candidates for spall repairs of airfield pavements. Their decision could depend on local factors and conditions for a particular airfield. The biggest threat spalls pose is in the form of Foreign Object Debris (FOD). Loose concrete chips and aggregates from a concrete spall have the potential to be sucked into jet engines, or damage propellers and rotors of million dollar aircraft. Spalls also increase the roughness of the pavement, possibly to the point that the pavement becomes damaging to the landing gear of fighter aircraft. Sharp edges from spalling concrete also have the potential to cut aircraft tires.

1.2 Background

If conducted under the constraint of time, expediently repaired spalls are a form of Rapid Runway Repair (RRR). Air Force Civil Engineers have trained on and performed RRR since the days of World War II. During this time, engineers constructed wooden plank runways in the Pacific as a quick means of establishing airfields. This method was soon replaced with a newer innovation known as Pierced Steel Planking (PSP). PSP consists of an interlocking steel matt made lighter by its pierced holes. PSP, along with other materials such as Hessian Matting and Square Mesh Track (SMT) were also used in World War II. An interlocking aluminum mat known as AM-2 matting was used extensively in both the Korean and Vietnam Wars. AM-2 matting is heavy, labor intensive and not feasible for some of the aircraft in our current Air Force inventory.

The Cold War highlighted the need for advances in RRR. If the enemy were to spall or crater airfield pavements with bombs, our ability to launch aircraft sorties would be crippled. In the 1990's, a lightweight alternative to AM-2 known as Folded Fiberglass Matt (FFM) was introduced. Unlike AM-2 however, FFM is merely a FOD cover. Since it is not a structural material, it requires an underlying structural repair before it is installed. A repair alternative is needed that can be made quickly with little effort, and meet the requirements of modern aircraft and manpower constraints.

1.3 Problem Identification

There are many different products on the market today that are advertised as suitable for PCC spall repair. Each of these is characterized by many different engineering properties. With so many properties that will determine its success in producing a long lasting repair, the decision of

which one to use becomes difficult. Although one material may excel in certain respects, it may be lacking in others. Finding the clear winner is difficult, and will ultimately depend on the performance characteristics that produce the best results for the decision maker. For example, in cases where the repair does not need to be ready for traffic immediately after placement, the decision maker would place little importance on the material's early strength. Therefore, a decision tool is needed that can be tailored to each decision maker's unique situation. This tool would rank order repair-material alternatives based on the importance that the decision maker places on the objectives of runway repair and pavement repair materials. The military decision maker would then have a tool to allow him or her to choose the best repair material for the airfield at his or her installation.

Another advantage to this tool will be the identification of new materials that are suitable for testing. Prior to fielding spall repair materials for wartime use, materials often undergo testing by research agencies within the DOD. These agencies include the Air Force Civil Engineer Support Agency (AFCESA), the Air Force Research Lab (AFRL), and the US Army Corps of Engineers Waterways Experiment Station Engineering Research and Development Center (USACE WES ERDC). However, field testing can be expensive, time consuming, and requires special equipment. Because there is an abundance of concrete repair products on the commercial market, a decision tool is needed to determine which products are worthy of testing and which are not.

1.4 Research Questions

In order to create an effective decision-making tool, the following research questions will be addressed by this study:

1. What are the characteristics that engineers look for in an ideal repair material?
2. What characteristics and properties are uniquely important to military engineers in the repair of airfield pavements?
3. What is the appropriate methodology for choosing the best pavement repair material?
4. What are the available materials suitable for concrete spall repair?
5. Which material(s) should military engineers select for concrete pavement spall repair?

1.5 Research Approach

Evaluating different repair materials may be difficult because each has different strengths and weaknesses. In order to compare these materials on the same scale, this research will create a decision tool that allows the decision maker to assign his or her own values, risk preferences, and objectives to determine which repair alternative is best in his or her situation. The methodology that does this best is Value Focused Thinking (VFT). VFT is a strategic, quantitative approach to decision making that uses specified objectives, evaluation measures, and value hierarchies (Kirkwood, 1997). VFT follows a process of five steps when faced with decision problems: recognize a decision problem, specify values, create alternatives, evaluate alternatives, and select an alternative. VFT is different from traditional approaches because traditional methods look for alternatives before considering values. Once values are specified, evaluation measures are determined to effectively score the alternatives. A single-dimensional value function is then created to compare the scores of each alternative on the same scale. The alternative with the highest score will be selected as the best alternative.

1.6 Scope

Alternatives will be chosen for this model that best fulfill the decision maker's objectives in the value hierarchy. However, because testing is limited on some repair material properties, the alternatives chosen may be limited to those with complete data on the value hierarchy measures. In addition, repair materials for asphalt pavements are not considered; this research is restricted to the selection of repair materials intended for PCC pavements only. Furthermore, only partial-depth (occurring in the top one third of pavement thickness) spall repairs will be considered. Another limitation to this model is that the weights are assigned subjectively, and may differ from the weights of the end user.

1.7 Significance

By employing this tool to select the best repair material for airfield pavements, military decision makers will be able to make quality repairs that best suit their situation. This model will predict the best material to use when faced with many repair products available on the market. The model will also serve as a tool to assist engineers in choosing which of these materials should undergo the cost of additional field testing.

In today's Global War on Terrorism, US forces are encountering airfield pavements on foreign airbases in less-than-ideal shape. Civil Engineer crews are conducting spall repairs on a daily basis, during times when runways are shut down specifically for this purpose. Currently, Pavemend© is the predominant spall repair material in use by Civil Engineer crews on foreign airfields. The question of whether this material is best is still not clear-- crews have experienced early failures with this material. Figure 2 shows a pavement repair that has failed. The reason for

this failure could be caused by conditions not favorable for its use. This decision tool will pick the best repair material given the conditions engineer crews will face.

Figure 2. Example of a Failed Concrete Pavement Repair

1.8 Summary

This research will provide a systematic, objective way for military engineers to choose the best concrete repair material for use on airfield pavements. The model will address the unique needs of military engineers faced with this decision by applying a value-focused thinking methodology. Maintenance of runways on foreign airbases involves daily spall repair to maintain an acceptable surface for US aircraft. This thesis will determine the best material(s) for producing long-lasting, trouble free repairs.

II: Literature Review

2.1 Overview

Many techniques have been used in the past to solve construction maintenance and repair decisions. This chapter will first examine past methodologies that have been used to solve pavement maintenance and other construction related decisions. Next, traditional methods for testing and comparing concrete repair materials will be investigated, along with a look at the qualities and properties that are needed for repair materials to produce a long lasting repair. Finally, this chapter will introduce the multiple objective decision making method known as Value-Focused Thinking.

2.2 Decision Analysis Approaches

2.2.1 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process was developed by Thomas Saaty (1990:1-39) as a way to decompose a complex problem into a series of one on one comparisons. This method is first approached by decomposing the problem into a hierarchy of criteria and alternatives. Next, pairwise comparisons are made to determine the importance of one criterion over another. These comparisons are then arranged into a matrix. By calculating an eigenvector from this matrix, one can determine the rankings of priorities. This gives the weights of the values in the hierarchy. Next, pairwise comparisons are made against the alternatives for each respective value. This

information is then placed into a matrix, and the eigenvector calculated. The eigenvector gives the rankings for the alternatives for a particular value. The summation of the alternative's value ranking times the respective weights for each value gives the final score for each alternative. The alternative with the greatest score is the best alternative (Saaty 1990).

Miroslaw Skibniewski and Li-Chung Chao (1992) demonstrated the Analytical Hierarchy Process's usefulness to the construction industry by showing how it can quantify the intangible benefits of new or advanced construction technologies along with the risks of implementation. With this process, the attributes of a new and existing construction technology are compared pairwise according to the decision maker's knowledge and experience. Likewise, the relative importance of each criterion is determined by the decision maker's judgment and perception (Skibniewski, 1992:580). In Skinbiewski's example, a semiautomated tower-crane is compared against a traditional tower-crane. In their example, the semiautomated crane achieved a slightly higher score against the traditional crane. However, if a different decision maker were to go through this process, the outcome may change.

2.2.2 Life Cycle Cost Analysis (LCCA)

The American Institute of Architects (AIA) defines a life cycle cost analysis (LCCA) as "The calculation of expected future operating, maintenance, and replacement costs of designs and features to assist owners in developing a realistic design and budget estimate" (AIA, 2006). Al-Mansour and Sinha (1994) used the LCCA technique to make pavement maintenance decisions on deteriorating asphalt pavements. They considered four options for rehabilitating a pavement: do nothing, perform Basic Routine Maintenance (BRM), perform BRM and chip sealing, or perform BRM and sand sealing.

By performing a present worth analysis for all alternatives, the most economical maintenance alternative was determined. Additionally, the authors used available data to develop a set of pavement condition prediction models to determine the effectiveness of maintenance activities. Data was also used to determine the relationship between a pavement serviceability index (PSI) and age. Using statistical regression, the authors found that:

$$PSI = a + b*Age \quad (1)$$

Where
PSI = pavement serviceability index
Age= pavement age (in years) since construction or last resurfacing
a,b = estimated regression parameters

Using the same method, the authors found that the gain in PSI due to seal coating follows the below relationship:

$$\Delta PSI = a*(PSI - b) \quad (2)$$

Where
ΔPSI = gain in pavement serviceability due to seal coating
PSI = PSI at time of seal coating
a, b = estimated regression parameters

By using a computer program to perform the LCCA, the authors were able to experiment with the cost variations caused by varying the PSI at which resurfacing was performed. They concluded that the optimal timing to perform sealing from a cost standpoint occurs when the PSI reaches a value of 3.25. They recommend that BRM should be performed along with seal coating, but seal coating should not be postponed beyond a PSI value of 3.0. They did not find any major cost difference in comparing chip sealing vs. sand sealing. (Al-Mansour, 1994)

2.2.3 Expert Systems

An expert system is an interactive, problem-solving software program that emulates the knowledge of a human expert in a specific area. Ritchie et al., (1986) developed an expert system named SCEPTRE 1.1 to make flexible pavement rehabilitation strategies for state-maintained highways. To begin the program, the user selects one of six forms of pavement distresses: 1. Corrugation, waves, sags, and humps, 2. alligator cracking, 3. raveling or flushing, 4. longitudinal cracking, 5. transverse cracking, 6. patching. Once the particular type of pavement distress is chosen, the program asks the user to answer a set of categorical questions about the condition of the pavement. For example, if alligator cracking is selected as the type of pavement distress, the program requests the following inputs, summarized in Figure 3:

TABLE 1 SCEPTRE Knowledge-Base Levels for Alligator Cracking in Wheelpath(s)

Level	Description
1. Climate	Region A: marine-dominated climate Region B: high solar radiation, temperature extremes
2. Amount of surface distress	Based on percent length of both wheelpaths distressed: 1. <10% 2. 10% < amount < 25% 3. >25%
3. Severity of surface distress	1. Hairline cracking 2. Spalling or spalling and pumping
4. Existing pavement performance	Based on predicted or actual life to a rating score of 40[a]: 1. <5 years 2. 5 < performance < 10 yr 3. >10 yr
5. Traffic levels	1. ADT < 800 veh/lane 2. 800 ≤ ADT ≤ 4,000 veh/lane 3. ADT > 4,000 veh/lane
6. RAMs	See list in text

[a] Pavement life is the time since original construction or the last resurfacing to a pavement condition rating of 40 (based on a scale of 0 to 100).

Figure 3. Variable Inputs on SCEPTRE 1.1 Program (Ritchie, 1986:100)

Once these questions are answered, the program generates a set of Rehabilitation and Maintenance Strategies (RAMs). Expected service life and the associated probability the pavement will exceed this life are shown in the output (see Figure 4)

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

YOUR MINIMUM DESIRED RAM SERVICE LIFE FOR THIS SECTION IS 5 YEARS.
IN THE OUTPUT BELOW, P IS THE PERCENT PROBABILITY THAT THE ACTUAL SERVICE
LIFE FOR EACH RAM WILL BE AT LEAST THIS LONG.

THE LIST OF FEASIBLE STRATEGIES FOR THIS PAVEMENT SECTION IS AS FOLLOWS:

DO-NOTHING                      P =  0% (EXPECTED LIFE = 2 YEARS)
FOG SEAL                        P = 25% (EXPECTED LIFE = 3 YEARS)
THIN ASPHALT CONCRETE OVERLAY   P = 37% (EXPECTED LIFE = 4 YEARS)
MEDIUM ASPHALT CONCRETE OVERLAY P = 75% (EXPECTED LIFE = 7 YEARS)

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

Figure 4. SCEPTRE 1.1 Expected Pavement Service Life Output (Ritchie, 1986:102)

Expert systems are ideal to use for problems that meet the following criteria:

-Algorithmic solutions are impractical because of complex physical, social, political, or judgmental components
-Experts exist in the field
-An expert is not physically available
-Tasks are largely cognitive
(Ritchie, 1986:97)

Expert systems differ from conventional computer programs in that an explicit problem-solving algorithm is not needed since every knowledge element is already stored and outputted depending on the user responses to the initial questions. To state this another way, human experts have programmed the software to output a particular RAM depending on the combination of pavement condition inputs by the user. This makes the software useful as a learning tool, and to pass on acquired wisdom of senior transportation engineers to others in the Department of Transportation (DOT).

An Expert System was later developed in 1994 by Khan et al. (1994:1-16) to gather data from California Department of Transportation engineers, and determine design features and project scope for resurfacing, restoration, and rehabilitation (RRR) pavement projects. The Expert System was designed to prevent underestimation of project-costs, which was frequently occurring on projects expanded to include RRR safety enhancements. The program allowed Caltrans (California DOT) engineers to input data from both office records and field assessments into the software. The software can then recommend design features and an appropriate project scope by accessing data from past projects. Use of this tool helps Caltrans engineers develop more accurate project cost estimates.

2.3 Property testing and field performance of repair materials

Research on concrete repair materials has not revealed any exact methodologies to follow for choosing the best repair material for a particular application. Instead, it has focused on the performance properties of the material, and attempts have been made to correlate these properties with durability and crack resistance of repairs. According to P.H. Emmons et al., leading researchers in the concrete repair field, there are two difficulties with selecting repair materials; the lack of industry-wide reliable testing standards, and the lack of generally accepted performance criteria (2000:38). This section will review the current state of research on the performance and selection criteria of concrete repair materials.

Although this section describes the properties that are considered important for the selection of a good repair material, it should be emphasized that these properties should be looked at as a whole—any one single property will not determine the success and durability of a

repair. It should also be noted that the selection of a repair material is only one of many interrelated steps needed to produce a quality repair. Equally important are the method of application, surface preparation, construction practices, and follow on inspection (Emmons 1994:43). The influence diagram in Figure 5 shows the interrelationship of factors that affect the durability of a concrete repair system.

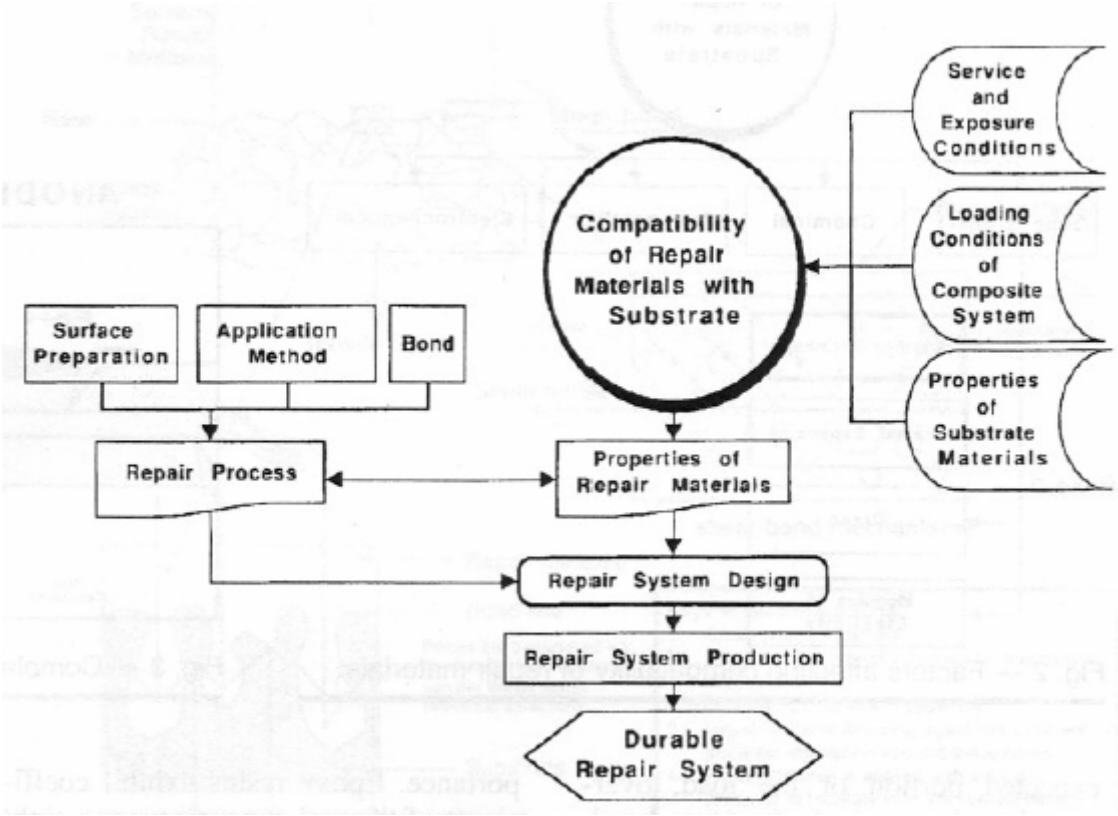

Figure 5. Factors Affecting Durability of a Concrete Repair System (Emmons, 1994:43)

Spalling, cracking, scaling and loss of strength are all symptoms of durability problems within a concrete repair system. Depending on the structure to be repaired and the type of damage, the reason for the repair may vary. However, Edward Rizzo and Martin Sobelman (1989:46) identified three basic requirements that a repair material should fulfill: 1. The repair must arrest the deterioration of the structure. 2. The repair must restore the structural integrity,

and have strength properties similar to those of the substrate. 3. The repair must provide an esthetically acceptable finish. In the case of pavement repair, esthetics, mentioned in the third requirement, should be of little importance. The first and second requirements however, agree with the nature of pavement repairs. One could also argue there is an additional requirement of restoring smoothness to the pavement.

2.3.1 Material Properties

2.3.1.1 Compatibility

Compatibility is regarded as one of the most important factors in producing durable repairs. As shown in Figure 6, compatibility is the balance of physical, chemical, permeability and electrochemical properties and dimensions between the repair material and existing substrate.

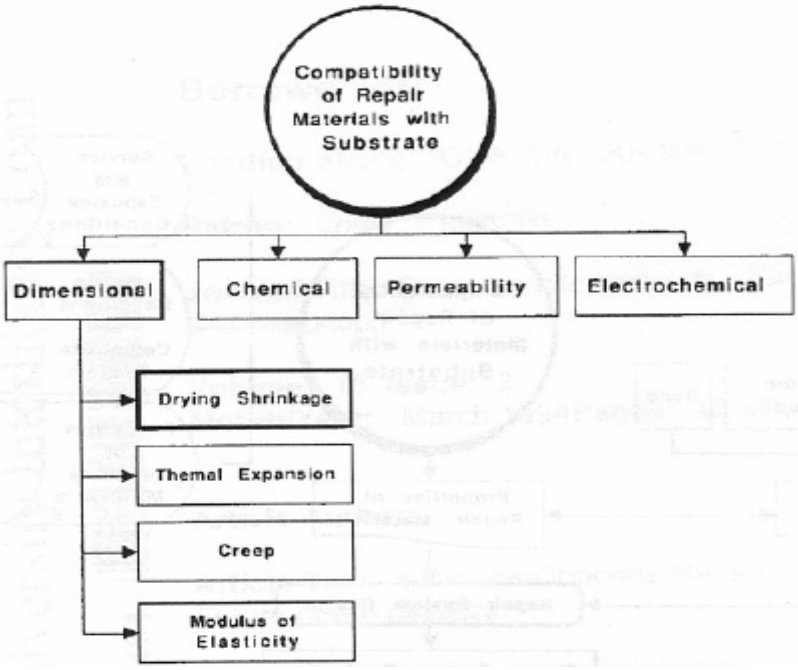

Figure 6. Properties that Affect Compatibility between Repair Material and Substrate (Emmons, 1994:44)

Dimensional compatibility refers to the volume changes of the repair material and substrate. It is the focus of most research done on the properties of repair materials. This is because dimensional incompatibility between the repair material and substrate is believed to cause the majority of problems in concrete repairs. This incompatibility adversely affects the durability of the repair and the load carrying capacity of structural repairs. (Emmons 1994:43) Most of the property tests of dimensional compatibility are standardized under the American Society for Testing and Materials (ASTM).

There are four factors that makeup a material's dimensional compatibility: drying shrinkage, thermal expansion, creep, and modulus of elasticity. Drying shrinkage is the contraction of a material as moisture is removed by evaporation to the outside. This contraction causes strain-induced loading, and may lead to cracking. Cracking occurs when the induced tensile stress exceeds the tensile capacity of the material (Emmons, 1994:44). Drying shrinkage can be categorized as either restrained or unrestrained. Restrained shrinkage causes more strain externally and internally compared to a material in free shrinkage. For this reason, most shrinkage tests are of the restrained variety, since this causes the worst case induced strains on a material. In practice, materials are seldom subjected to a free shrinkage scenario. The bond to the existing substrate restrains the repair material as it is contracting. This is yet another reason why the restrained shrinkage test is used.

The "ring test" is a common method for determining whether cracks will form in the material as it dries. Although it is a non-standard test, Poston, et al (2001:140) conducted the ring test in this manner: The material was cast around a ten inch diameter, one inch thick steel pipe. The material ring was four inches high, and one and one quarter inch thick. The mold was removed after twenty-four hours; thereafter, it was monitored daily for evidence of cracks. The

day that cracking was first observed was recorded. This test has now been standardized as ASTM C1581-04.

Repair materials, like most any material, will expand and contract with changes in temperature. If the coefficients of thermal expansion of a repair patch and substrate are too dissimilar, high stress will develop at the bond interface. This may ultimately result in bond failure and the ejection of the repair patch from the spall. Ideally, the coefficient of thermal expansion should match that of the existing substrate. (ACI Committee 546, 2006:6) Coefficient of thermal expansion testing is done in accordance with the ASTM C 531 procedure.

Creep is defined as the time-dependent inelastic deformation occurring with prolonged application of stress (Emmons, 2000:38). A repair material may experience tensile creep caused by drying shrinkage, or it may experience compressive strength from structural loads. Although it is generally accepted that higher creep aids in the relaxation of stresses and strains caused by restrained shrinkage, a study by McDonald et al (2002:42) found the opposite to be true. In their study, there was improved field performance in materials with decreased creep. They attributed this in part to the higher drying shrinkage of materials with high creep characteristics (McDonald, 2002:42). Regardless, in an airfield pavement-repair scenario, one would not expect to have a prolonged application of stress, except in the case where an aircraft tire might park on top of a repair. A pavement repair would be more likely to see cyclic stresses from moving aircraft. However, as Emmons points out, "very few tests, if any, to date, have incorporated stress or cyclic stress on the specimen concurrent with exposure to the environment" (Emmons, 2000:42).

Modulus of elasticity, also known as Young's modulus, is defined as the slope of the curve that represents stress divided by strain. In non-structural applications, it is generally

agreed that decreases in modulus of elasticity reduces the potential for cracking of cement-based repair materials. This is attributed to creep and stress relaxation of lower modulus materials reducing the magnitude of stresses induced by drying shrinkage (McDonald, 2002:40). However, in structural applications where the repair material will see a point load, as in pavements, differences in Young's modulus between the substrate and repair patch may lead to stress concentrations (Emmons, 1994:44). In this case, the bond region is the weak link and cracks will tend to form there. It is best to select a repair material that will best match the modulus of the existing substrate. This will help ensure a uniform load transfer across the section (Rizzo, 1989:48).

Chemical compatibility generally refers to the alkali content, C_3A content (tricalcium aluminate), and chloride content of the repair material. As an example, if a concrete being repaired included potentially reactive aggregates, a repair material with low alkalinity must be specified. The reactivity of the material to reinforcing steel must also be considered; a material with a low pH may damage reinforcement by corrosion. Electrochemical compatibility may be a problem in the case where a potentially anodic metal area is overlaid. Increasing the cathode/anode area ratio could accelerate the corrosion process. In this case, methods for restricting excess water and oxygen in the cathodic area should be considered. (Emmons, 1993:41)

2.3.2 Other Properties of Concern

When choosing a repair material, there are other important properties beyond compatibility with the substrate. These other properties include freeze/thaw resistance, compressive strength, early compressive strength, and bond strength.

Concrete and other cementitious materials are susceptible to damage in environments that experience freeze/thaw cycles. Problems with freeze/thaw cycles can manifest in three ways: random cracking, surface scaling, and joint deterioration from durability cracking (d-cracking). D-Cracking often occurs along pavement joints. When water (usually from precipitation or contact with moist subgrade) penetrates concrete and freezes, it expands and causes high pressures. When this pressure exceeds the tensile strength of concrete, the concrete will crack (in the form of d-cracking) or scale. The most common way to prevent this cracking is through the use of air entrainment. Air entraining admixtures create a matrix of tiny (<0.01 inches) bubbles within the cement paste. These bubbles take on water during the freezing cycle to relieve pressure buildup (NRMCA, 2004). Selecting aggregates that perform better under freeze/thaw conditions, or reducing the aggregate size will help prevent D-cracking under these conditions (PCA, 2006).

Early strength may be of concern if a concrete pavement repair must be completed and ready for traffic in a short time period. At a minimum, the material would need a compressive strength equal to or greater than the tire pressure of the traffic it sees, to prevent the material from failing in compression. However, other properties such as shear strength, flexural strength, and tensile strength are correlated with compressive strength. Therefore, the compressive strength would need to be higher when subjected to actual traffic loads; engineers at the Air Force Civil Engineer Support Agency (AFCESA) use a weighted load cart to test repair materials by simulating traffic loads. Early strength is measured in compressive strength in accordance with ASTM C 39 procedures. There is no standard time at which early strength is recorded, but manufacturers often list it in the 3-4 hour range. Standard compressive strength is usually specified by engineers at the 28-day mark. This reference point was chosen because concrete

will have gained roughly 90% of its strength by this time. 28-day strength is also tested using ASTM C 39. The units for both are in pounds per square inch (psi) or megapascals (MPa).

Bond strength is important for ensuring a repair patch does not debond or delaminate from the substrate. Bond strength is tested in accordance with ASTM C 882, also known as the slant shear test. The test is conducted by forming a three inch diameter, by six inch high cylindrical mold. Within the mold is the repair material, bonded to ordinary portland cement. The bond line is thirty degrees from vertical, forming an elliptical area where the two meet. This specimen is then tested in compression. The stress is calculated as the maximum force applied, divided by the bond area where the two materials meet (ETL, 2006).

2.4 Decision Analysis

According to Clemen and Reilly (2001:2-3), there are four sources of difficulty that make solving problems hard. The first is complexity. A decision may have many alternatives, many courses of outcome, different economic impacts, and different values held by key players in the decision. Keeping all of these issues in mind may be nearly impossible. By using decision analysis, a complex problem can be arranged into a structure that can be analyzed. (Clemen & Reilly, 2001:2)

The second cause of difficulty in decision making is due to the inherent uncertainty of certain situations. Imagine a decision that involves choosing between two concrete repair materials—one that has good resistance to freeze/thaw conditions, and another that does not. Depending on the climate, there may be uncertainty as to how many freeze/thaw cycles the repair will experience. Decision Analysis can aid in identifying sources of uncertainty, and representing it in a systematic and meaningful way (Clemen & Reilly, 2001:3).

Another difficulty in decision making arises when there are multiple objectives in a decision. In this case, progress in one objective, may impede progress in another. This would force the decision maker to tradeoff benefits in one area to benefit another. Decision analysis provides a framework and tools for dealing with problems that have multiple objectives (Clemen & Reilly, 2001:3).

The last source of difficulty according to Clemen & Reilly (2001:3) is when different perspectives lead to different conclusions. This source of difficulty is pertinent when more than one person is involved in the decision making process. Different individuals may look at the problem from different viewpoints and disagree on the uncertainty of values of the outcomes. Decision analysis can help resolve these differences whether the decision maker is an individual or group (Clemen & Reilly, 2001:3).

Keeney (1993:5-6) describes decision analysis as a five step process: preanalysis, structural analysis, uncertainty analysis, utility or value analysis, and optimization analysis. Preanalysis occurs when the decision maker identifies a problem, the alternatives are given, and the course of action is unknown. The decision maker structures the qualitative anatomy in the structural analysis step. In the uncertainty analysis step, the decision maker assigns probabilities to the components of a problem with uncertainty. In the utility or value analysis step, the decision maker's unique risk attitude and mindset towards costs and benefits are quantified. In the final step, optimization analysis, the decision maker calculates the optimal decision strategy (Keeney, 1993:5-7).

2.4.1 Value-Focused Thinking (VFT)

The purpose of this section is to introduce one particular decision analysis tool known as Value-Focused Thinking (VFT). Shoviak (2001:63) distilled the concepts of VFT into a ten-step process, as shown in Figure 7below.

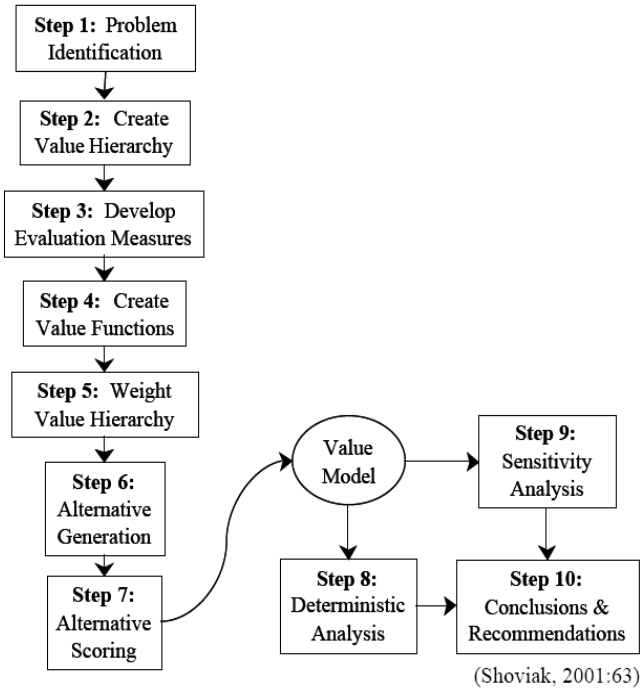

Figure 7. VFT Ten-Step Process (Shoviak, 2001:63)

In step one, the problem to be solved must be identified. Stated another way, a decision with alternatives must exist, and of the alternatives, only one can be selected. As Kirkwood (1997:2) points out, "If you don't have alternatives, then you may have a problem, but it isn't a decision problem."

The next step is to create a value hierarchy. A value hierarchy presents a visual way to structure the considerations that the decision maker feels are important to the decision. Kirkwood (1997:12) describes it as "tree-like," with its roots on the top, and branches on the bottom. Figure 8 shows a sample value hierarchy. A value hierarchy contains evaluation considerations, objectives, and evaluation measures. An evaluation consideration is any matter

that is significant enough to be taken into account in the evaluation of alternatives (Kirkwood, 1997:11). For example, evaluation considerations for someone purchasing a house may include proximity to work, size, and age. The tiers of a value hierarchy show the relative importance of the evaluation considerations; the considerations of highest importance are at the top of the hierarchy.

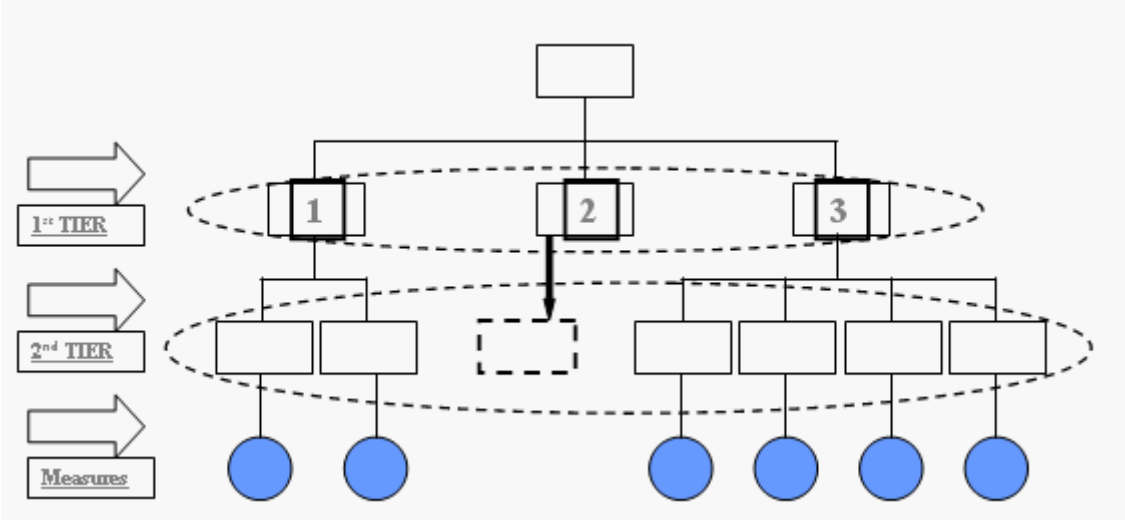

Figure 8. Hierarchy Tiers (Kirkwood, 1997)

The next step is to develop evaluation measures. Evaluations measures are "A measuring scale for the degree of attainment of an objective (Kirkwood, 1997:12)." Square footage may be an evaluation measure for a home buyer's objective of size. In the next step, single dimensional value functions (SDVF) are created for each measure. SDVFs account for measures in which there are increasing or decreasing "returns to scale" as a score on a measure moves in a preferable direction (Kirkwood, 1997:60). In the example of purchasing a home, a home buyer may assign a higher jump in value as the age of a home decreases from 10-5 years, than he would as age decreases from 5-0 years. SDVFs take into account cases like this where increasing scores moving in a preferable direction do not give a linear increase in value to the

decision maker. According to Kirkwood (1997:62-65), there are two types of SDVFs: piecewise linear and exponential. Figure 9 shows an example piecewise linear function. A piecewise linear function should be used when there are a small number of scoring levels (Kirkwood, 1997:61). When scoring levels can take on an infinite number, an exponential SDVF should be used (Kirkwood, 1997:64). Figure 10 shows example exponential SDVFs.

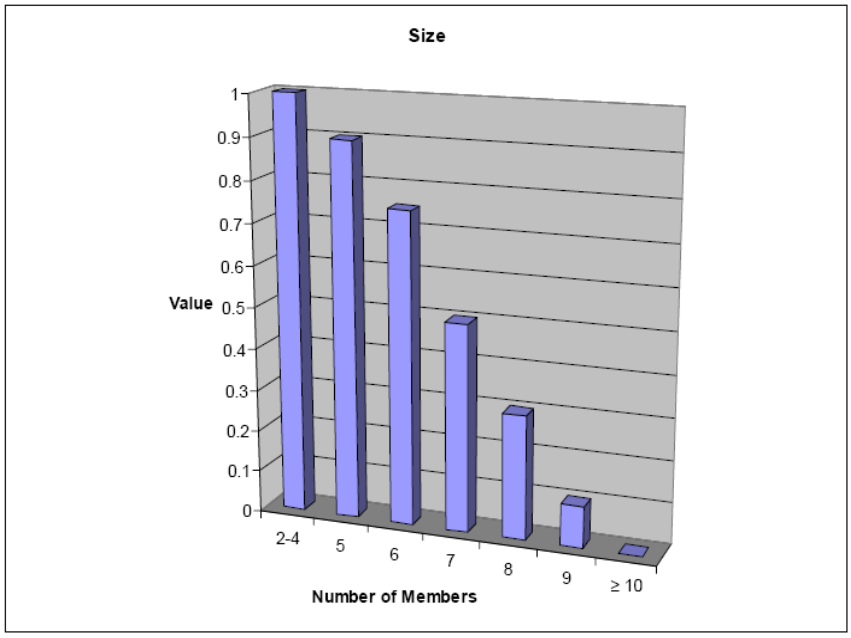

Figure 9. Example Piecewise Linear Function

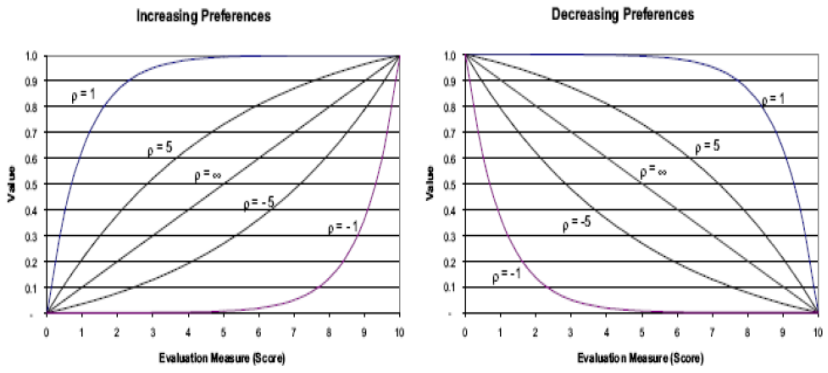

Figure 10. Example Exponential SDVFs

In the next step, the decision maker determines the weights of the values in the hierarchy. There are two ways to approach this. The first method is to weight all values in the hierarchy so

they sum to one. In this case, each value's weight would be considered a global weight, and would determine how each value impacts the overall decision. Another way to apply weights is by weighting the values on the same tier of the hierarchy, known as local weights. All local weights on the same tier must add to one. As the decision maker moves to lower tiers on the hierarchy, the local weights should sum to the weight placed on their respective value at the higher tier.

The next two steps in the VFT process are alternative generation and alternative scoring. One of the advantages of the VFT process is that it helps to bring forth previously unconsidered alternatives. The hierarchy process helps a decision maker structure what is important in his/her mind, and this may reveal new alternatives. Once the alternatives are known, they are scored according to the following equation:

$$Score = \sum_{i=1}^{n} w_i v_i(x_i) \tag{3}$$

Where: $v_i(x_i)$ = the value of the score on the i^{th} measure
and w_i = the weight of the i^{th} measure
and n = the total number of measures

In step 8, deterministic analysis is conducted by ranking the scores of all alternatives. Alternatives with higher scores are preferred. Sensitivity analysis is performed in step 9. Sensitivity analysis can determine the impact on the ranking of alternatives when changes to the model are made (Kirkwood, 1997:82). A sensitivity analysis on weights is often of interest. This particular analysis would show the how the ranking of alternatives might change if the weights were varied. In the final step, conclusions and recommendations are made to the decision maker regarding the findings of the model.

III. Methodology

3.1 Overview

Finding the best spall repair material for the job is often difficult, given the many choices in available products, and wide variability in performance on criteria that engineers consider important to the decision. This chapter will present the process of creating a VFT model to aid decision makers in ranking available spall repair products for use in airfield pavements. The decision makers in this process were pavement engineers from various organizations in the Department of Defense. These organizations include the Air Force Civil Engineer Support Agency (AFCESA), the Air Force Research Laboratory (AFRL), and the US Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC). Because this thesis used more than one decision maker, creation of the hierarchy, weight assignment, and construction of value functions required that a consensus was reached on each. In the case where requirements may change in the future for spall repair scenarios, this process can be adapted and repeated to meet changing missions.

3.2 Problem Identification

The first step in the VFT process is to identify the problem to be solved. Military engineers conducting spall repairs at overseas airbases are seeing varied success in the longevity of repairs. In many cases, early failures are seen in these repairs. These failures may be due to the use of inferior spall repair products, not suitable for the unique requirements of military

engineers maintaining airfield pavements. A decision tool is needed to identify spall repair products suitable for this application. Although this tool is not meant to replace actual field testing of products, it will be helpful in narrowing down from a wide list of products, those that are suitable to be tested in the field. Because field testing is costly and time consuming, this tool is needed to aid in identifying products that are good candidates to be tested in this manner, and eliminate those that are not.

3.3 Constructing the Value Hierarchy

A value hierarchy serves as a graphical representation for what is important to decision makers in a particular decision. Keeney (1992:24) identifies many benefits for using value-focused thinking, as shown in Figure 11.

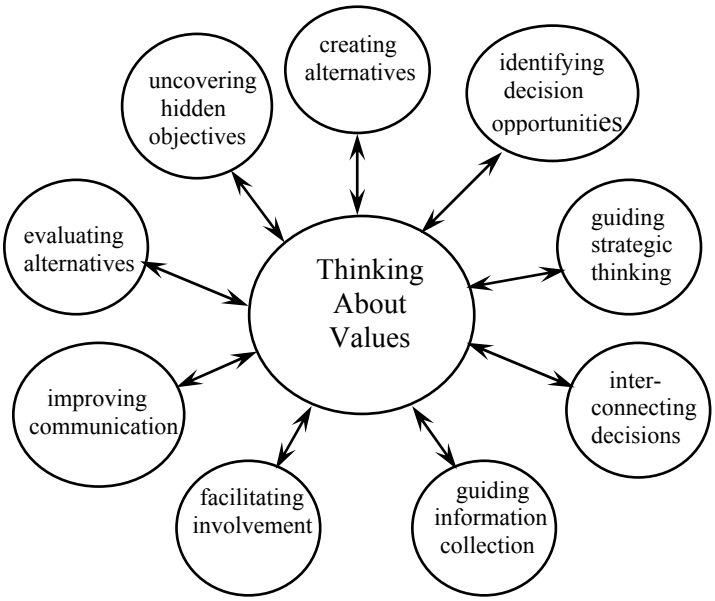

Figure 11. Advantages to using VFT (Keeney, 1992:24)

According to Kirkwood (1997:16-18), a hierarchy should be complete. A complete hierarchy is one that takes into account all concerns necessary to evaluate the overall objective of

the decision. A hierarchy should also be non-redundant, meaning it should not have any two evaluation considerations in the same tier that overlap. A good hierarchy is one that is decomposable and independent. In any situation where the value attached to variations in the level of one evaluation measure depends on the level of another measure, the measures are not decomposable and independent. This can cause problems when attempting to develop a procedure to combine evaluation measures to determine the overall preference of alternatives (1997:18). A hierarchy that is operable is one that is easily understood by the persons who use it. This is important for repeatability of the process—the hierarchy must be easily understood by future stakeholders in order to repeat the process. Finally, all other things being equal, a hierarchy should be small in size. This makes it easier to communicate, and requires fewer resources to estimate the performance of alternatives with respect to the evaluation measures (1997:18).

To begin the hierarchy, each of the decision maker's viewpoints on what was important to this decision had to be gathered. The decision makers were asked to provide values (issues of importance) from an engineer's perspective on necessary criteria to produce quality repairs. Additionally, decision makers were asked to consider what would be important from an end-user's perspective—in this case, that of the workers in the field performing the repair. By contacting the decision makers by telephone, each gave his thoughts on the matter. Construction of the hierarchy was an iterative process; as decision makers provided input on values and measures that belonged in the hierarchy, it was sent for review to the other decision makers until all were in agreement.

All agreed that the five most important values are low cost, desirable engineering properties, long shelf life, minimal site preparation required, and good workability. These values

are arranged on the first tier of the hierarchy, as shown in Figure 12. Table 1 defines each of the values on the first tier. The term "goal" as used in the hierarchy is synonymous with value.

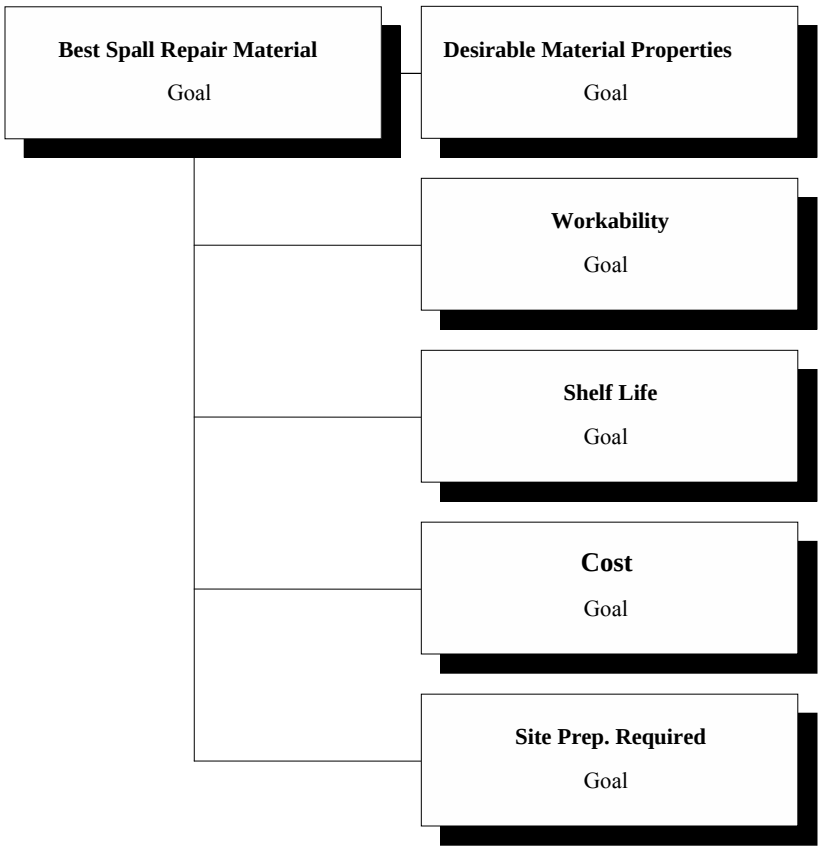

Figure 12. First Tier Hierarchy Values

Table 1. Definitions of First Tier Values

Desirable Engineering Properties	The physical and mechanical properties of repair materials necessary to produce quality, long-lasting repairs
Good Workability	The relative ease in which materials are prepared and placed
Long Shelf Life	The length of time a material can be stored without loss in performance
Low Cost	The total monetary cost of a material
Minimal Site Preparation Required	The amount of preparation required on the worksite prior to material placement

In the process of creating a value hierarchy, values should be subdivided into lower tiers until the lowest measurable objective is reached. Most of the first tier values can be subdivided further. The next sections provide details on the values and measures below the first tier of the hierarchy.

3.3.1 Cost

The decision makers brainstormed two values to define the first tier value of cost: direct cost and requirement for specialized aggregates. The direct cost is simply the cost of a repair product for a given yield of material. Requirement for specialized aggregate was chosen to capture the additional cost required when a repair product requires a special aggregate to be mixed with the product. Figure 13 shows the hierarchy branch for cost.

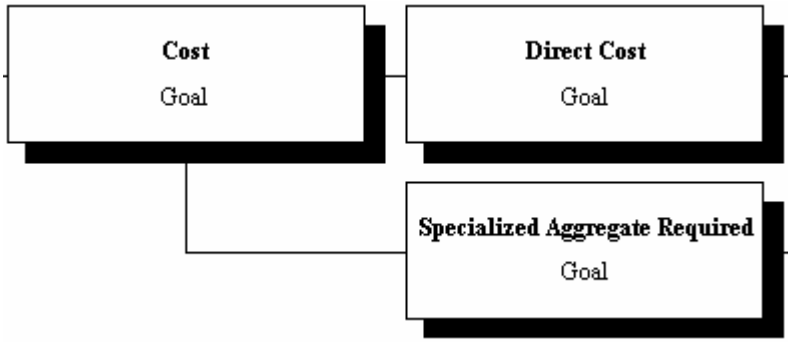

Figure 13. Cost Branch

3.3.2 Desirable Material Properties

The decision makers agreed that the Desirable Material Properties value will be further divided into seven values on the second tier of the hierarchy. Each of these values cannot be further subdivided, and will therefore terminate with a measure. Figure 14 shows the values and measures for the Desirable Material Properties branch. Table 2 defines the values and explains why the decision makers believe these are important to the decision.

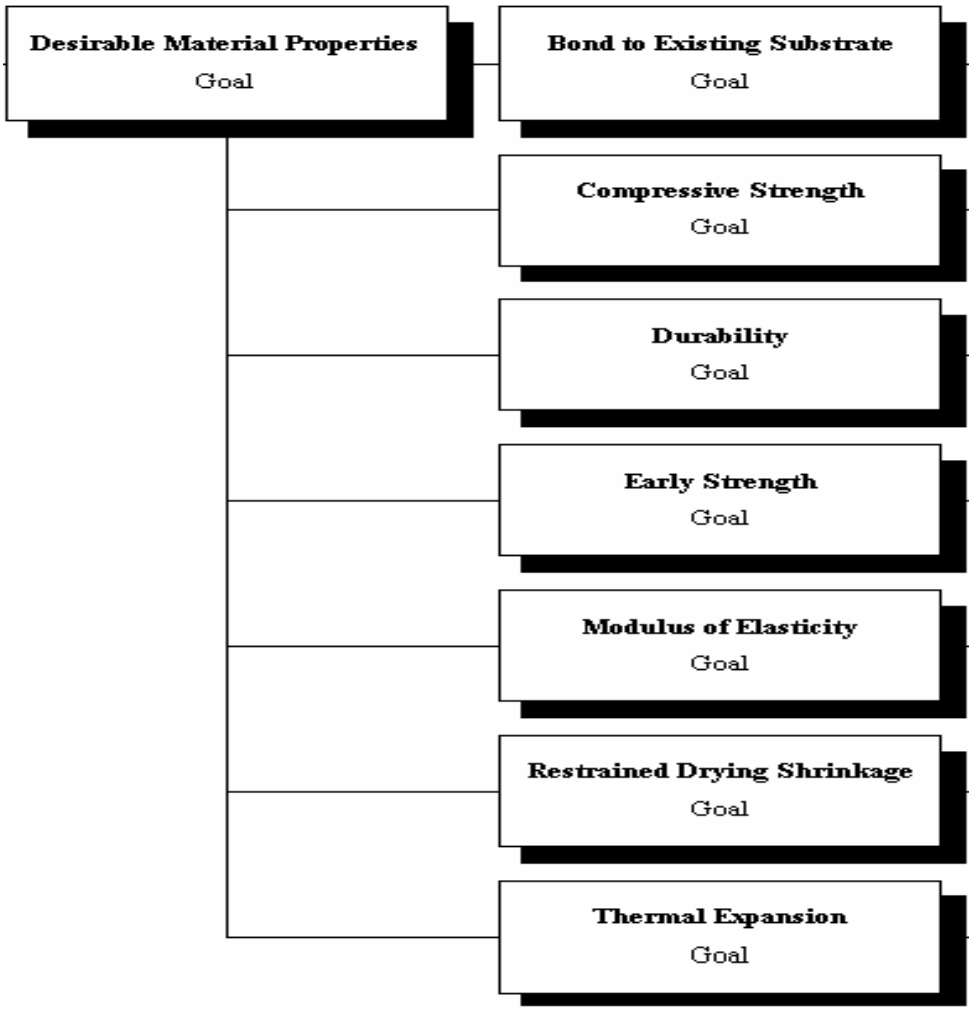

Figure 14. Desirable Material Properties Branch

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Table 2. Desired Material Properties Values

Value	Why Important
Bond to existing substrate	A material should bond well to the existing pavement to prevent delaminating and patch removal
Compressive Strength	Compressive Strength must be greater than the tire pressure of aircraft to prevent failure. In addition, other properties such as tensile and flexural strength are correlated with compressive strength. In the case where the modulii of elasticity are dissimilar for the two materials, these other properties become important to prevent failure
Durability	Durability refers to a materials resistance to weathering action, chemical attack, abrasion, and other degradation processes
Early Strength	Same as compressive strength above, but refers to a materials strength shortly after placement. This may become important in contingency scenarios where a material must be ready for traffic in a short time period
Modulus of Elasticity	This refers to the slope of a material's stress/strain plot, or in other words, its stiffness. An ideal material should match the modulus of the existing substrate, to ensure uniform load transfer
Restrained Drying Shrinkage	An ideal material should have zero shrinkage while drying under restrained conditions, as in a repair patch. Shrinkage can cause early cracking due to induced tensile stresses
Thermal Expansion	An ideal material should match the coefficient of thermal expansion of the existing substrate. Any differential in thermal expansion can cause stresses that lead to cracking

3.3.3 Shelf Life

Shelf life is located on the first tier of the hierarchy, since it cannot be classified under any other value. The decision makers believe shelf life is important because it determines how long a material can be warehoused before use. In a contingency scenario, it may be a long time before new materials can be delivered. Therefore, materials may need to be stockpiled to avoid shortages due to problems in delivery. Materials with long shelf lives can be stored and less effort will be needed to rotate stocks. See Figure 15 for the shelf life branch of the hierarchy.

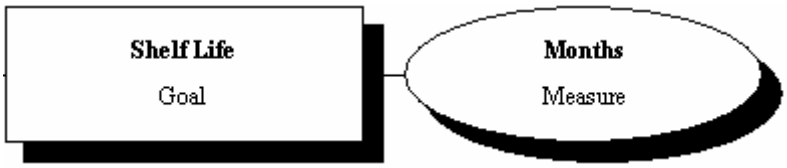


Figure 15. Shelf Life Branch

3.3.4 Site Preparation Required

The decision makers felt that an ideal material would require as little worksite preparation as possible. Increased site preparation adds more work and time to complete the job. The decision makers identified two variables in site preparation seen when placing spall repairs. The first is whether or not a repair material requires a bonding agent. Preparing and placing a bonding agent coat to the existing substrate adds a step to the repair process, and is not preferred if avoidable. The second variable found when using spall repair products is whether or not the product is hydrophobic. A hydrophobic material must be placed on a dry substrate. Drying the substrate can potentially add a considerable amount of work and time to the repair. The substrate could be damp at times from weather conditions or wet saw cutting. Figure 16 shows the branch for Site Preparation Required.

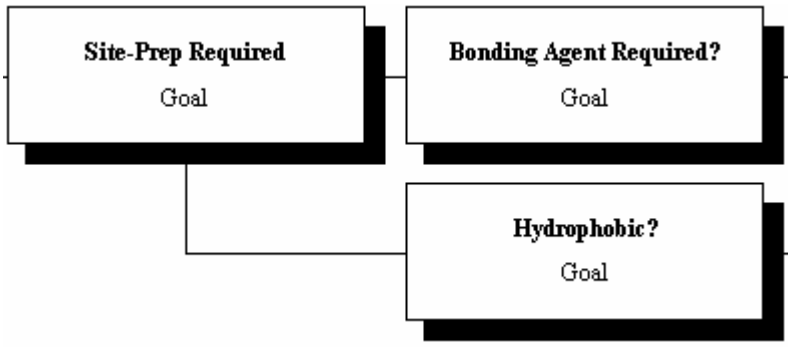


Figure 16. Site Preparation Required Branch

3.3.5 Workability

The last branch of the hierarchy captures the importance of material workability. Workability represents the relative ease in which a material can be mixed and placed. The decision makers included two values on the hierarchy to define a material's workability. The first value considers whether or not a material requires aggregates or must be placed in lifts. Some materials generate excess heat due to an exothermic chemical reaction once mixed. This heat can cause accelerated shrinkage and drying. To avoid this, some manufacturers require a material to be extended with aggregates, or placed in lifts for repairs that are deeper than a given depth. This is not desirable, since it requires a source of aggregates or an increase in time to place multiple lifts. The second value that subdivides workability is working time. Working time is the amount of time a work crew has before a material becomes stiff, and therefore unable to place or trowel for a smooth finish. Figure 17 shows the hierarchy branch for workability.

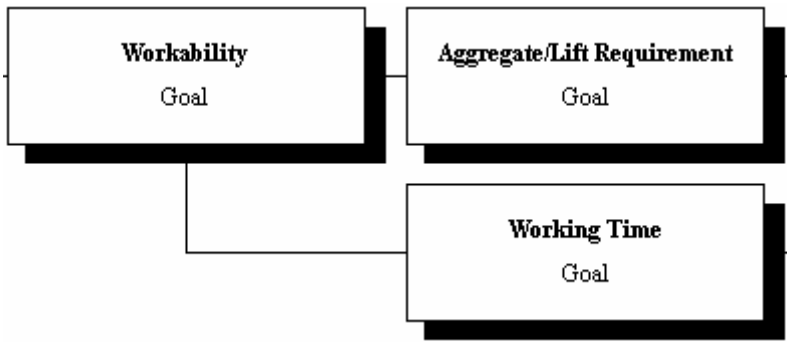


Figure 17. Workability Branch

3.3.6 Complete Hierarchy

The complete hierarchy is shown in Figure 18. The decision makers were satisfied that the hierarchy is complete since it adequately covers all concerns necessary to evaluate the decision. The decision makers also felt there were no obvious signs of redundancy. Since the

hierarchy is complete and non-redundant, it can be said that the values in the hierarchy for this decision are "collectively exhaustive and mutually exclusive (Kirkwood 1997:17)."

The hierarchy does show limitations in decomposability. Looking at the cost values, a decision maker may be willing to pay more for a material that does not require specialized aggregates. Since the value attached to "direct cost" may vary with the level of "specialized aggregates required," an independence problem arises. This same situation occurs with "early strength" and "working time." Materials with high early strengths are likely to have shorter working time. Therefore, a decision maker may vary the value attached to working time depending on the level of early strength.

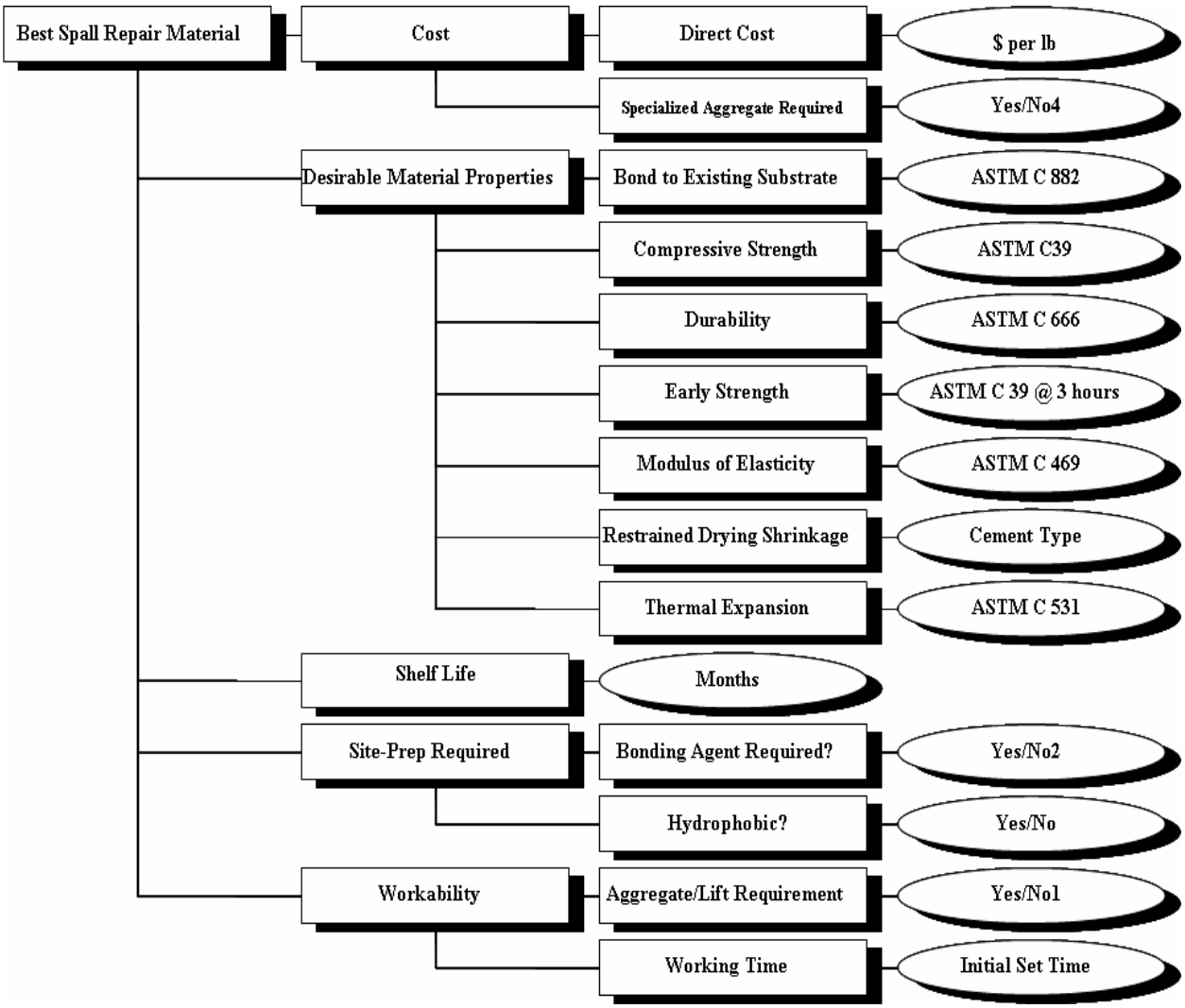


Figure 18. Complete Hierarchy

3.4 Develop Evaluation Measures

Each of the values has an associated measure, shown in the ovals to the right of the rectangular value boxes. The measures are used to quantify and score the alternatives performance on each of their respective values. According to Kirkwood (1997:24), measures are classified as natural or constructed, and as direct or proxy. Natural scales are those in general

use and commonly understood by everyone. The slump test, measured in inches concrete has "slumped" after having been removed from a cone, is a natural scale for evaluating the workability of concrete. Constructed scales are those that are uniquely developed for a particular decision problem, such as classifying concrete shrinkage as low, medium, or high. If a measure is a direct scale, it directly measures the level of attainment of an objective, as in measuring the shelf life of a repair product in months. A proxy measure on the other hand, reflects the degree of attainment of an associated objective. Cement type is a proxy measure for the shrinkage of a cementitious repair material. It should be noted that the determinations of natural versus constructed and direct versus proxy are not absolute. In reality, they represent the extremes on a wide range of possibilities (Kirkwood, 1997:24).

3.4.1 Cost

Direct cost will simply be measured by the cost per weight of material. Since the yield in volume of repair material will vary with water/cement ratio, aggregate extension etc, a simpler measure of cost per weight of material will be used instead. For example, if a fifty pound sack of material costs $100, the direct cost is $2/lb. Cost per weight of material is a natural, proxy measure. Requirement for specialized aggregates is a categorical, binary measure of yes or no. This measure is natural and direct.

3.4.2 Desired Material Properties

Table 3 lists the values and their associated measures. The units of the evaluation measures and type of scale are also shown in the table.

Table 3. Desired Material Properties Measures

Value	Measure	Units	Scale
Bond to existing substrate	ASTM C 882, Standard Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete By Slant Shear	PSI	Natural/Direct
Compressive Strength	ASTM C 39, Compressive Strength of Cylindrical Concrete Specimens	PSI	Natural/Direct
Durability	ASTM C 666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing	% of modulus of elasticity retained after freeze/ thaw cycles	Constructed/Proxy
Early Strength	ASTM C 39, recorded at 3 hours	PSI	Natural/Direct
Modulus of Elasticity	ASTM C 469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression	PSI	Natural/Direct
Restrained Drying Shrinkage	The predominant mineral of the material's cement composition will be used as a proxy measure for restrained shrinkage	Categorical (Low, Medium, High)	Constructed/Proxy
Thermal Expansion	ASTM C 531, Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes	in/in°C	Natural/Direct

3.4.3 Shelf Life

Shelf life is simply measured by the manufacturer's specified shelf life in months. It is a natural and direct measure.

3.4.4 Site Prep Required

The measures for "bonding agent required" and "hydrophobic" are both binary, categorical measures with responses of yes and no. They are both natural and direct measures.

3.4.5 Workability

The measure for "aggregate/lift requirement" is a natural, binary measure with responses of yes or no. "Working time" is measured by a material's initial set time. The initial set time is determined by the Vicat needle method. The test procedure for this method is as follows: A weighted, 1mm needle is lowered into cement paste. The time it takes until the needle penetrates 25mm into cement paste is recorded as the initial set time. This measure is direct and proxy for working time.

3.5 Weighting the Hierarchy

Weights can be applied to the value hierarchy in a global or local manner. If local weighting is chosen, the decision maker assigns weights to a particular tier in a branch so that the weights sum to one. These are also known as relative weights, since the weights only hold true relative to the other values in the same tier and branch. Another approach is to assign weights globally. With this method, the decision maker directly assigns weights to all values in the hierarchy, so that all weights on the lowest level values add to one. The decision makers for this thesis decided to assign global weights directly to the values in the hierarchy.

Because the decision for this thesis is choosing the best spall repair material for military applications, the decision makers felt the weights in the hierarchy were dependent on the repair scenario. They asserted that the weights would change depending on whether the repair was performed in a conventional, steady state operational environment, or if the repair was conducted in a contingency environment. The decision makers defined a conventional repair scenario as one made without the constraint of time. Specifically, they assumed that the repair will not be

subjected to traffic within six hours after placement. A contingency repair scenario was assumed to be one that was required to be ready for traffic in under six hours after placement. Given a contingency environment, some values were more important, and some less. Therefore, the hierarchy was weighted two ways to be pertinent to both scenarios. Table 4 shows the weighting for a conventional work environment, and Table 5 shows the weighting for a contingency scenario.

Table 4. Weight Assignments for Conventional Spall Repair

Conventional			
Tier 1		**Tier 2**	
Value	**Weight**		**Weight**
Cost	0.15	Direct Cost	0.100
		Specialized Aggregates Required	0.050
Material Properties	0.45	Bond to Existing Substrate	0.050
		Compressive Strength	0.050
		Durability	0.050
		Early Strength	0.000
		Modulus of Elasticity	0.050
		Restrained Drying Shrinkage	0.200
		Thermal Expansion	0.050
Shelf Life	0.05		
Site Prep Required	0.10	Bonding Agent Required	0.050
		Hydrophobic	0.050
Workability	0.25	Aggregate/Lift Requirement	0.050
		Working Time	0.200
Total	1.00		

Table 5. Weight Assignments for Contingency Spall Repair

Contingency			
Tier 1		**Tier 2**	
Value	**Weight**		**Weight**
Cost	0.05	Direct Cost	0.000
		Specialized Aggregates Required	0.050
Material Properties	0.50	Bond to Existing Substrate	0.050
		Compressive Strength	0.050
		Durability	0.050
		Early Strength	0.050
		Modulus of Elasticity	0.050
		Restrained Drying Shrinkage	0.200
		Thermal Expansion	0.050
Shelf Life	0.05		0.050
Site Prep Required	0.15	Bonding Agent Required	0.075
		Hydrophobic	0.075
Workability	0.25	Aggregate/Lift Requirement	0.050
		Working Time	0.200
Total	1.00		

3.6 Creating Value Functions

In order to rank repair material alternatives using the VFT process, a Single Dimension Value Function (SDVF) must be created for each evaluation measure. An SDVF determines the value or "goodness" that a decision maker assigns for a particular level of an evaluation measure (Kirkwood, 1997:55). The SDVF assigns the worst possible level of an evaluation measure a

score of zero, and the best possible level for an evaluation measure a score of one. By "normalizing" the levels of evaluation measures to a unitless scale from zero to one, the overall score of an alternative can be found using Equation 1, the additive value function (described in Chapter 2):

$$Score = \sum_{i=1}^{n} w_i v_i(x_i) \qquad (3)$$

The additive value function sums the product of each measure's SDVF score and its respective weight. The overall score for an alternative will fall between zero and one; an alternative with a maximum score on each evaluation measure would receive an overall score of one, and an alternative with a minimum score on each evaluation measure would receive an overall score of zero. The alternative with the highest overall score is chosen as the best alternative.

The SDVFs for each measure must be monotonically increasing or decreasing. A monotonically increasing value function is one in which higher values on a measure are preferred by the decision maker. Similarly, monotonically decreasing functions are those for which lower values on evaluation measures are preferred. In the case of continuous functions, increasing functions have positive slopes, and decreasing functions have negative slopes.

The SDVFs used in this model are discrete or continuous. The discrete SDVFs are categorical, meaning they have a finite number of levels (categories), while the continuous SDVFs have an infinite number of possible levels. The decision makers chose a discrete or continuous scale for each evaluation measure. For those measures that were evaluated on a discrete scale, categories were determined and given an associated value. If a measure was determined to be continuous, the decision makers were asked to provide an upper and lower bound representing the best and worst possible scores. The decision makers chose to use linear,

rather than exponential functions for all continuous functions; they reasoned that research correlating material properties with field performance is still in its early stages, and not enough is known to predict anything more sophisticated than a linear relationship. The decision makers based the reference points and categories for the value functions on their personal knowledge and experience testing and working with repair materials. The decision makers held the value functions constant for both conventional and contingency weighting. The next sections will show and describe the SDVFs for each measure in the hierarchy. All SDVFs were created using the software program *Logical Decisions for Windows*.

3.6.1 Cost Value Functions

The first cost measure, cost per yield, is a measure of the cost of a material for a given yield. The units chosen for this measure are US dollars per cubic foot of material. This function is continuous because cost can take on an infinite number of values. It is monotonically decreasing since high cost is not preferable. The decision makers chose a lower bound of $1 per cubic foot, and an upper bound of $200 per cubic foot of material. Figure 19 shows the Cost per Yield SDVF.

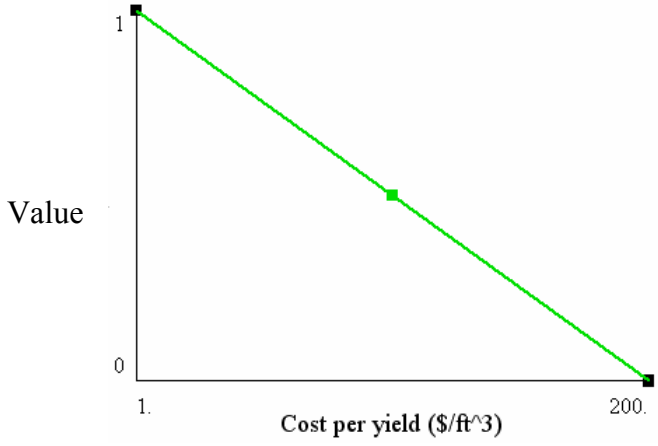


Figure 19. Cost per Yield SDVF

The second measure specifies whether a repair material requires a specialized aggregate. This SDVF is categorical since the range of possibilities is binary. A repair material that does not require specialized aggregates receives the full score of one on this measure. Figure 20 shows the categorical SDVF.

Figure 20. Requires Specialized Aggregates SDVF

3.6.2 Desirable Material Properties Value Functions

The ASTM C 882 slant shear bond test measures a repair materials ability to resist sliding between a material and the concrete substrate. The units for this measure are pounds per square inch (PSI). The decision makers chose a continuous, linear function with an upper bound of 3000 PSI and lower bound of 1500 PSI. The function is increasing since higher bond strengths are preferred. Figure 21 shows the ASTM C 882 SDVF.

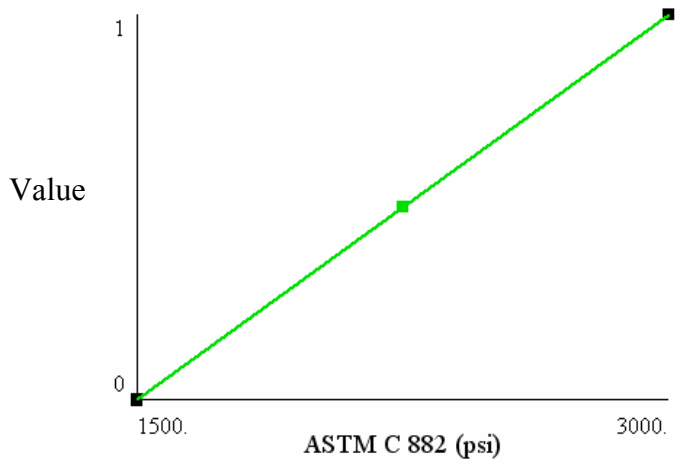


Figure 21. ASTM C 882 SDVF

ASTM C 39 measures the compressive strength of a material specimen. This test represents the strength of a material after 28 days of curing. The units for this measure are PSI. The decision makers chose a linear, continuous function with an upper bound of 10000 PSI and a lower bound of 2500 PSI. The function is increasing since higher compressive strengths are preferred. Figure 22 shows the ASTM C 39 SDVF.

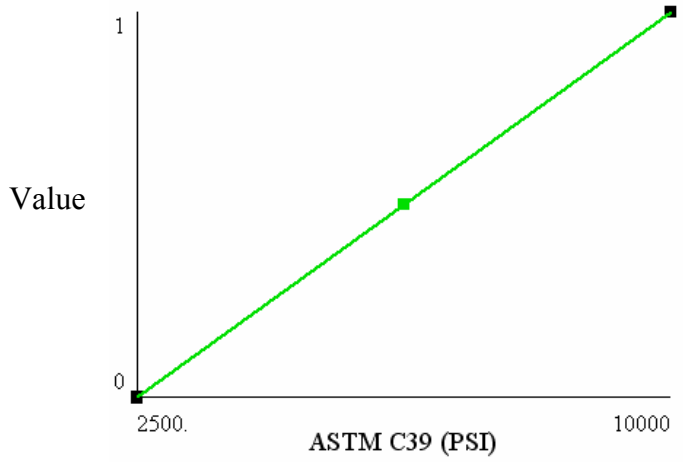


Figure 22. ASTM C 39 SDVF

ASTM C 666 is a standard test to determine the durability of a material when subjected to freeze/thaw cycles. To begin the test, a material's dynamic modulus of elasticity is first measured. Next, the material is subjected to 300 freezing and thawing cycles. After the test, the change in the materials dynamic modulus of elasticity is recorded. The unit for this measure is the percentage of dynamic modulus retained after the test. This test uses a continuous function since there is an infinite range of values for percent dynamic modulus retained. The function is increasing since higher percentages of dynamic modulus retained represent more durable materials. The decision makers chose an upper bound of 80% and a lower bound of 0%. Figure 23 shows the ASTM C 666 SDVF.

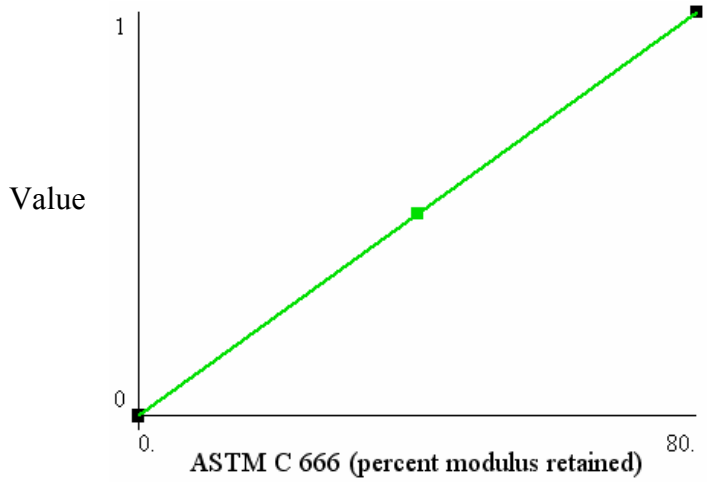
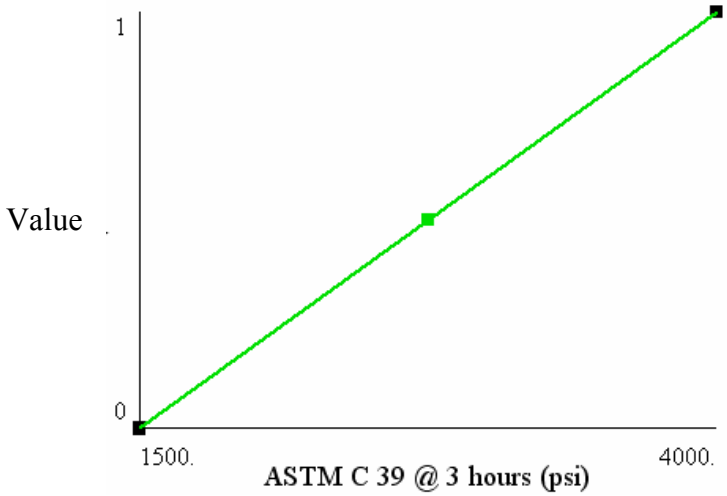


Figure 23. ASTM C 666 SDVF

Early strength is measured by the same test as compressive strength (ASTM C 39); To measure early strength however, this test is performed after three hours of curing instead of 28 days. The units for this test are PSI, and the function is continuous since the range of possible values is infinite. The function is increasing since high early strength is preferred. The decision

makers chose an upper bound of 4000 PSI, and a lower bound of 1500 PSI. Figure 24 shows the SDVF for early strength.



SDVF for Early Strength (ASTM C 39 after 3 hours of curing)

Modulus of elasticity is measured by ASTM C 469. This test measures the slope of a material's stress/strain curve when deformed, or in simpler terms, the stiffness of a material. The units for this test are PSI. The decision makers felt that an ideal material would have a modulus of elasticity equal to that of the concrete substrate. The levels of modulus of elasticity for alternatives will therefore be inputted in this model as the deviation, or delta from an assumed value of concrete pavement. The decision makers chose 4.5 million PSI as a typical value for concrete pavement. The value function for this measure will scale the modulus differential that deviates from 4.5 million PSI. The function is continuous since there is an infinite range of possible deviation values. The decision makers chose an upper bound of 4.5 million PSI, and a lower bound of 0 PSI (no differential from substrate). The function is decreasing because a high modulus differential from the existing substrate is not preferred. Figure 25 shows the SDVF for modulus of elasticity differential.

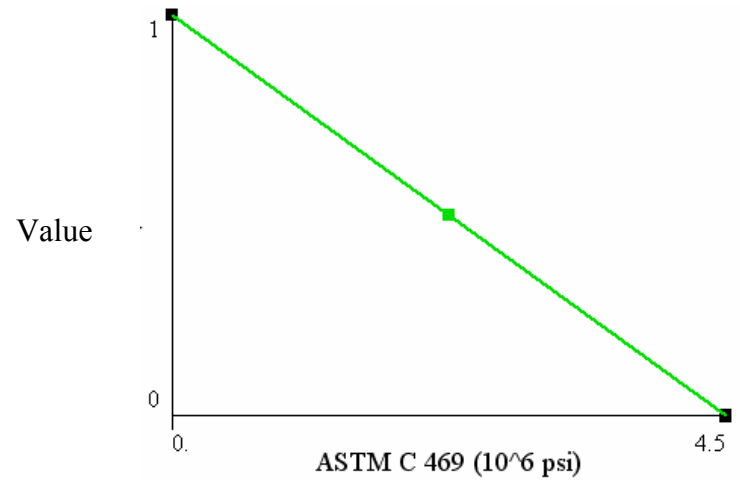


Figure 25. Modulus of Elasticity Differential from Substrate SDVF

Restrained drying shrinkage is a measure of the shrinkage a material will undergo while under restrained (confined) conditions. High shrinkage materials are avoided because of the potential for cracking while in the curing phase. A material's cement type was chosen as a proxy measure for this value. In general, materials that include calcium aluminate (C3A) or silica fume (SiO_2) as mineral components experience high shrinkage (Holt, 2001:175). Materials with magnesium phosphate as their primary cement component have low shrinkage. Materials with Portland cement as their primary cement component will be classified as medium shrinkage. The value function for this measure is categorical, with possible value of low, medium, and high. The function is decreasing since high shrinkage is not preferred. Figure 26 shows the categorical SDVF for restrained shrinkage.

Figure 26. Restrained Shrinkage SDVF

ASTM C 531 measures a material's coefficient of thermal expansion. The coefficient of thermal expansion is the rate at which a material expands or contracts to changes in temperature. The units for this test are microstrains per degree Fahrenheit. A microstrain is the length in millionths of an inch that a material will shrink or swell per each inch of length. The decision makers felt that an ideal material would have a coefficient of thermal expansion similar to that of the concrete substrate. Any differential between the two can cause movement fluctuations, and negatively affect the performance of the repair (ACI, 2006:6). The typical range of values for thermal coefficients of portland cement concrete is typically 2 to 8 microstrains/° F (ACI, 2006:7). The decision makers chose 5 microstrains/°F as an assumed value for concrete pavements. Therefore, the deviations from this value will be scaled using a continuous SDVF. The decision makers chose an upper bound of 5 microstrains/°F and a lower bound of 0 microstrains/°F (no differential). The function is decreasing since high thermal coefficient deviations are not preferred. Figure 27 shows the SDVF for thermal coefficient deviation.

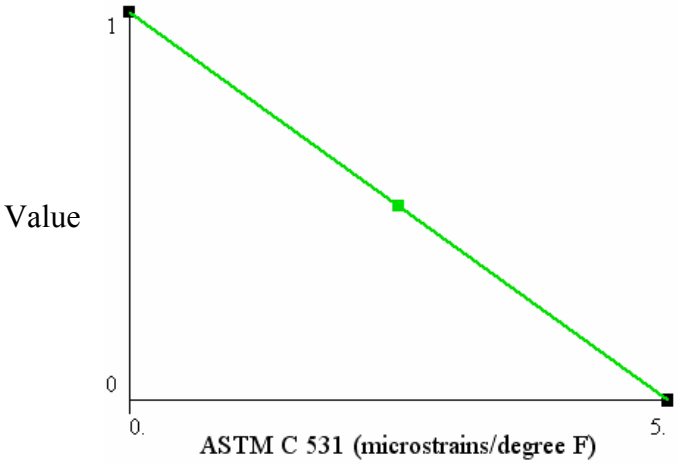


Figure 27. Thermal Coefficient SDVF (deviation from 5 microstrains/°F)

3.6.3 Shelf Life

The shelf life of a material is the length of time a manufacturer recommends a product can be stored unopened before the performance of a material is degraded. The unit for this measure is months. This function is continuous since the range of possible values is infinite. The function is increasing because materials with high shelf lives are preferred. The decision makers chose an upper bound of 60 months and a lower bound of 12 months. Figure 28 shows the SDVF for shelf life.

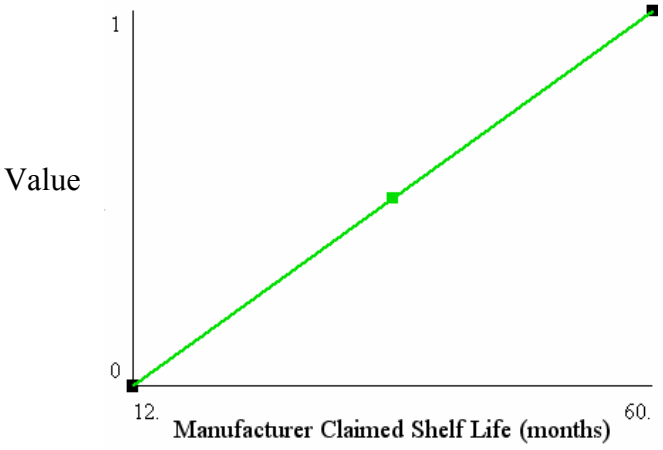


Figure 28. Shelf Life SDVF

3.6.4 Site Preparation Required

The first measure in the Site Preparation Required branch is the determination of whether a material requires a bonding agent or not. A bonding agent is not preferred because it adds a step to the repair process. The value function for this measure is binary and categorical. There are only two possible values for this function: yes or no. If the material requires a bonding agent, it receives a score of zero—otherwise, it receives a score of one. Figure 29 shows the SDVF for Bonding Agent Requirement.

Figure 29. SDVF for Bonding Agent Requirement

The second measure in this branch is the determination of whether a material is hydrophobic or not. Hydrophobic materials cannot be applied to damp or wet surfaces. Hydrophobic materials are not preferred because they cannot be placed in wet weather conditions, and require extra time and effort to dry a wet surface. The value function for this measure is binary and categorical. There are only two possible values for this function: yes or no. If a material is hydrophobic, it receives a score of zero—otherwise, it receives a score of one. Figure 30 shows the categorical SDVF for Hydrophobic.

Figure 30. SDVF for Material Hydrophobicity

3.6.5 Workability

The first measure for the Workability branch is the determination of whether a material requires that it be extended with aggregates or placed in lifts. Some materials require this when placed beyond a certain depth. The value function for this measure is binary and categorical. Only materials that require lifts or aggregates for depths under six inches will be considered to fail this requirement, since most partial depth spall repairs are less than six inches deep. If a material requires lifts or aggregates for depths less than six inches, it will receive a score of zero—otherwise, it will receive a score of one. Figure 31 shows the SDVF for Aggregate/Lift Requirement.

Figure 31. SDVF for Aggregate/Lift Requirement

The second measure in the Workability branch is initial set time. Initial set time is a measure of the working time engineers will have to place a material before it becomes hardened and unworkable. The decision makers felt an ideal initial set time is 45 minutes. Any deviation from 45 minutes will be scaled using the SDVF in Figure 32 below. The function is decreasing

since high deviation from the ideal set time is not preferred. The function is continuous because there is an infinite range of possible set times for a given material. The decision makers chose an upper bound of 45 minutes and a lower bound of 0 minutes (no differential).

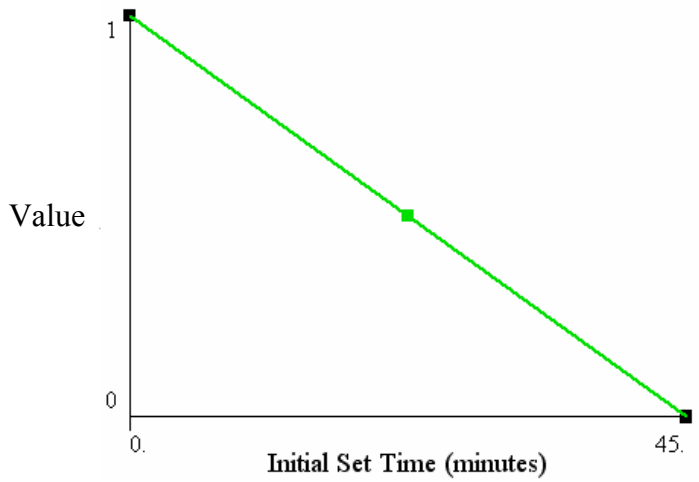


Figure 32. SDVF for Initial Set Time (deviation from 45 minutes)

3.7 Alternative Generation

Repair material alternatives were chosen by the decision makers from the many available repair products on the commercial market. The decision makers chose materials that were thought to best meet the important values that the decision makers conceptualized in the value hierarchy. Table 6 shows the repair materials that were chosen for this model. The repair material alternatives and their associated scores are presented in Chapter 4.

Table 6. Repair Materials Scored in Model

Product Name	**Manufacturer**
Set 45 HW	BASF Building Solutions
Set 45	BASF Building Solutions
FiveStar Highway Patch	Five Star Products
Five Star Structural Concrete	Five Star Products
Pavemend SL	CeraTech
Pavemend TR	CeraTech
Pavemend VR	CeraTech
Pavemend SLQ	CeraTech
Pavemend 15	CeraTech
Pavemend 5.0	CeraTech
Pavemend EX	CeraTech
Pavemend EX-H	CeraTech
ThoRoc 10-61C Rapid Cement	BASF Building Solutions
ThoRoc 10-60C Rapid cement	BASF Building Solutions

IV. Results and Analysis

4.1 Overview

This chapter will present and analyze the rankings of spall repair products using steps seven, eight and nine of Shoviaks's 10-step VFT process. In step seven, alternatives will be scored on each measure in the hierarchy. In step eight, deterministic analysis will reveal the rankings of repair products as calculated by the Logical Decisions software program. In step nine, sensitivity analysis will be performed to determine what impact changes in weights will have in the ranking of alternatives.

Since hierarchy weighting is different for conventional and contingency repair scenarios, deterministic analysis will be performed separately for each. However, because most repairs will be conducted in a conventional, steady state repair scenario, sensitivity analysis will be discussed for this weighting only.

4.2 Alternative Scoring

The primary source of data for evaluation measures in this hierarchy was collected from product manufacturer's websites. It should be noted that many engineers caution against relying on data supplied by manufacturers. In many cases, independent lab tests do not back up manufacturer's claims on the results of material properties. For this reason, any data that was available from independent testing was used in place of manufacturer data. As more data becomes available through independent lab testing, this model should be updated to maximize the integrity of the model. Table 7 is a summary of data collected on each of the evaluation

measures for the fourteen repair alternatives. All data except those in the shaded cells were collected from manufacturer specifications.

Table 7. Summary Matrix of Alternative Scores

Material Name	Set 45 HW	Set 45	FiveStar Highway Patch	Five Star Structural Concrete	Pavement SL	Pavement TR	Pavement VR	Pavement SLQ	Pavement 15	Pavement 5.0	Pavement EX	Pavement EX-H	ThoRoc 10-61C Rapid Cement	ThoRoc 10-60C rapid cement
Manufacturer	BASF Building Solutions	BASF Building Solutions	Five Star Products	Five Star Products	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	BASF Building Solutions	BASF Building Solutions
Cement Composition (in order of prominence)	Silica (crystalline quartz), fly ash, magnesium oxide	Silica (crystalline quartz), fly ash, magnesium oxide	Silicon Dioxide, Crystalline Silica, Silica Sand SiO2,	Silicon Dioxide, Crystaline Silica, Silica Sand SiO	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Magnesium oxide, Phosphate (calcium/ potassium/sodium), silica (crystalline quartz)	Magnesium oxide, Phosphate (calcium/ potassium/sodium), silica (crystalline quartz)	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	alumina cement, portland cement, anhydrite, fly ash	alumina cement, portland cement, anhydrite, fly ash
Shrinkage	Low	Low	High	Low	Low	Low	Low	Low	Low	Low	Low	Low	High	High
$/cf	$50.00	$50.00	$50.00	$70.00	$116.30	$116.30	$116.30	$116.30	$116.30	$116.30	$122.00	$116.30	$13.49	$13.49
Special Aggregates required?	Yes	Yes	No	No	Yes	No	No	Yes	No	N	Yes	Yes	N	N
Bond Strength (ASTM C 882 Slant Shear) @ 7 days	2190 psi	2250 psi	2000 psi	2500 psi	1665 psi	1930 psi	2400 psi	2866 psi	2000 psi	2780 psi	2450 psi	2500 psi	1480 psi	2160 psi
Early Strength (ASTM C 39 @ 3 hours)	3227 psi	5000 psi	3500 psi	2500 psi	3643 psi	3000 psi	4300 psi	3966 psi	3870 psi	3830 psi	2875 psi	3395 psi	3887 psi	3100 psi
Freeze/Thaw Resistance (ASTM C 666)	80%	80%	96%	>90%	>80%	>80%	>80%	>80%	>80%	>80%	>80%	>80%	100%	100%
Modulus of Elasticity (ASTM C 469)	4.90*10^6 psi	4.18*10^6 psi	3.5*10^6 psi	3.8 * 10^6 * psi	2.21* 10^6 psi	2.77* 10^6 psi	2.27* 10^6 psi	1.70* 10^6 psi	3.3* 10^6 psi	3.4* 10^6 psi	2.72* 10^6 psi	4.56* 10^6 psi	4.6*10^6 psi	4.4*10^6 pjsi
Modulus differential from 4.5 * 10^6 (10^6 psi)	0.4	0.32	1	0.7	2.29	1.73	2.23	2.8	1.2	1.1	1.78	0.06	0.1	0.1
Compressive Strength (28 Day)	6317 psi	8500 psi	7280 psi	8000 psi	4257 psi	7114 psi	6580 psi	7483 psi	6300 psi	6100 psi	5870 psi	6535 psi	8293 psi	6893 psi
CoefficientofThermal Expansion (ASTM C 531)	7.15 *10^-6	7.15 *10^-6	8.3* 10^-6	5*10^-6	2.55 *10^-6	2.52X10^-6	2.52X10^-6	2.95X10^-6	2.82 X 10^-6	2.95*10^-6	5.9* 10^-6	6.13 X 10^-6	6.8*10^-6	7.0 *10^-6
Thermal Coefficient Differential from 5 Microstrains (*10^-6)	2.15	2.15	3.3	0	2.45	2.48	2.48	2.05	2.18	2.05	0.9	1.13	1.8	2
Shelf Life	12 months	12 months	12 months	24 months	36 months	36 months	36 months	36 months	36 months	36 months	12 months	12 months	12 months	12 months
Requires Bonding Agent?	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Hydrophobic?	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Lifts or Aggregate required?	Yes	Yes	No	Yes	Yes	No	No	Yes	No	No	Yes	Yes	No	No
Initial Set Time	76 min	13 min	25 min	30 min	11 min	12.5 min	17.5 min	4 min	12.5 min	4 min	70 min	37.5min	193 min	20 min
Initial Set time Differential from 45 min (minutes)	31	32	20	15	34	32.5	27.5	41	32.5	41		7.5	148	25

Key:

Data collected from WES Repair, Evaluation, Maintenance, and Rehabilitation (REMR) reports

Data obtained from the Wisconsin Department of Transportation

Data obtained from WES ERDC lab testing

Data obtained from engineers at AFCESA

4.3 Deterministic Analysis (Conventional Weighting)

In Chapter 3, SDVFs were created for each evaluation measure to convert the scores in Table 7 into unitless, normalized values from zero (least preferred) to one (most preferred). Next, the scores from Table 7 were inputted into Logical Decisions and the software calculated the corresponding unitless value for each measure determined from the SDVFs created earlier. Logical Decisions then used the additive value function to sum the products of these values and their predetermined weights (see Tables 4 and 5) for each evaluation measure to compute a total score for each alternative. The software then ranked each alternative based on its score, from high to low.

4.3.1 Deterministic Analysis on a Conventionally Weighted Scenario

Figure 33 shows the rank ordered list of alternatives using the decision maker's weighting (Table 4) for a conventional repair scenario. Pavemend EX-H ranks the highest and earns the highest additive value function sum of 0.707.

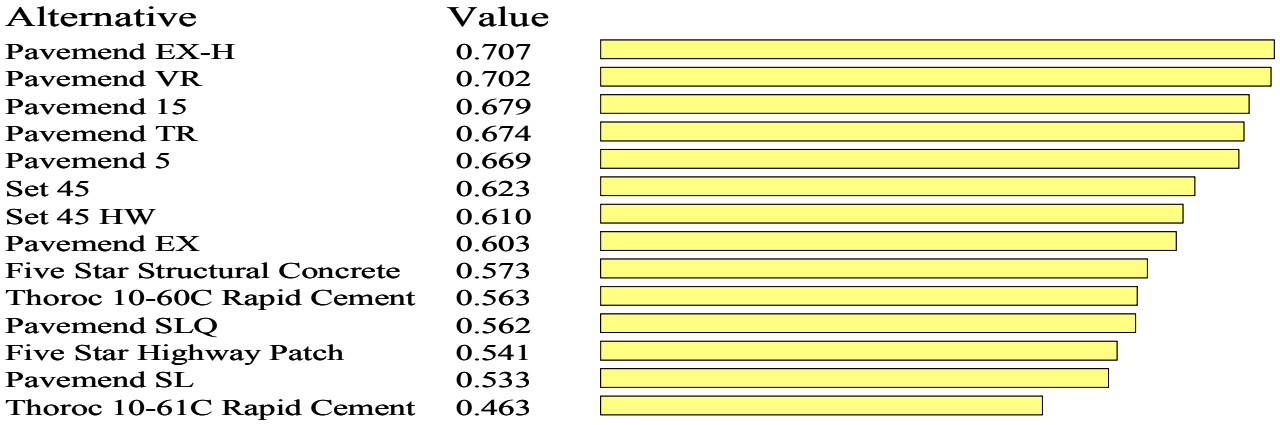


Figure 33. Alternative Rankings under Conventional Weighting

The value score next to each alternative specifies the distance (in a value sense) that each alternative is from the hypothetical best or worst score (Kirkwood, 1997:74). However, Kirkwood (1997:74) explains that no specific meaning can be given to value numbers without knowing the ranges of the evaluation measures being used. Therefore, the values next to each alternative should only be used to rank alternatives and not to infer a degree improvement from one alternative to another.

Figure 34 shows how well each alternative fulfilled the decision maker's fundamental objectives by color-coding the bands to indicate how well each alternative scored on the Tier 1 values. The lengths of the color coded bands are in proportion to the scoring for each respective value. This makes it easy to see how each fundamental objective contributed to the overall score of each alternative.

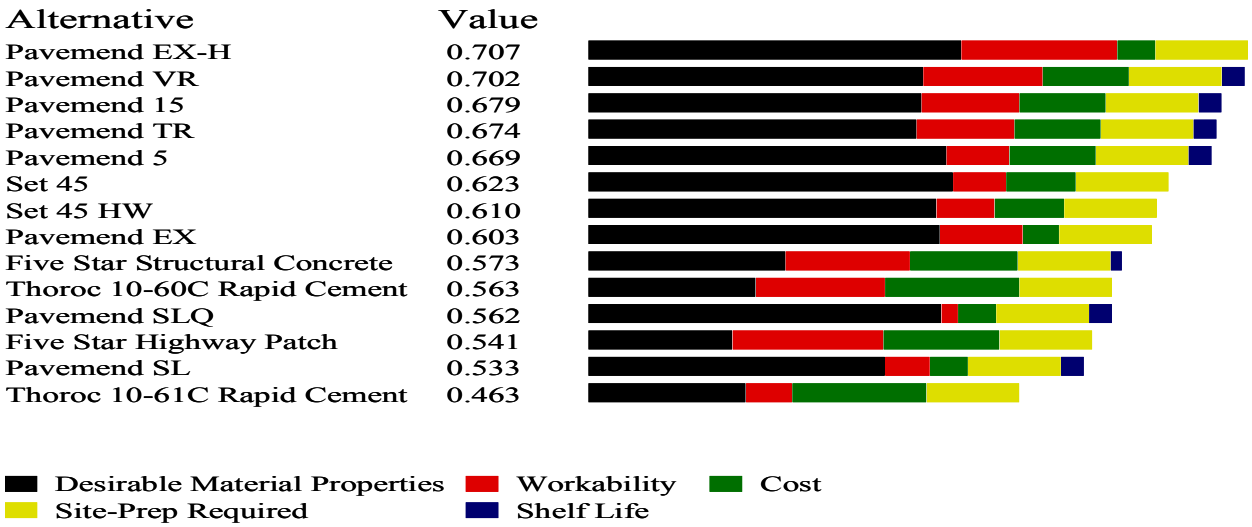


Figure 34. Alternative Rankings with Respect to Fundamental Objectives (Conventional Weighting)

The top choice, Pavemend EX-H, outscored all other materials on the Desirable Material Properties value. It also scored highly on the Workability and Cost values. Although it has a score of zero on Shelf Life, it scores well enough on all other values to earn the top spot on the list. Pavemend VR scored well on all fundamental objectives, but was edged out by Pavemend EX-H on Desirable Material Properties and Workability. The worst alternative, Thoroc 10-61C Rapid Cement, ranked at the bottom due to poor scores on Desired Material Properties and Workability, and because it received a score of zero on Shelf Life.

Logical Decisions can also perform a stacked bar ranking by color-coding each individual measure. Figure 35 shows the stakeholders how each measure hurt or helped the value score of each alternative.

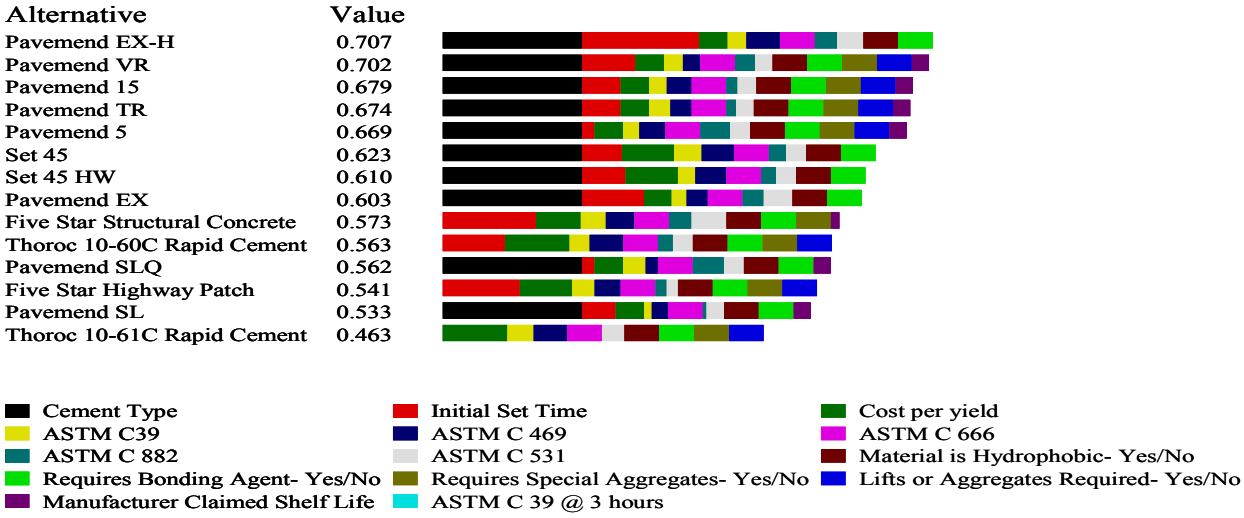


Figure 35. Alternative Rankings with Respect to Evaluation Measures (Conventional Weighting)

At the top of the list, Pavemend EX-H scores well on all measures within the Desirable Material Properties value. The next best alternative, Pavemend VR, is one of the few alternatives to score consistently well across all fourteen measures. In fact, only Pavemend VR, Pavemend 15,

Pavmend 5, and Pavemend TR received non-zero scores across all measures. Pavemend EX-H scores higher than the latter four due to its high score on Initial Set Time. The stacked bar ranking in Figure 35 does not show a score for early strength (ASTM C 39 @ 3 hours) for any alternatives since this value has a weight of zero under a conventional repair scenario weighting.

4.3.2 Contingency Weighting Deterministic Analysis

Figure 36 shows the rank ordered list of alternatives using the decision maker's weighting (Table 5) for a contingency repair scenario. Using this weighting, Pavemend VR becomes the dominant alternative. Although the order has changed, the same materials remain the top five alternatives.

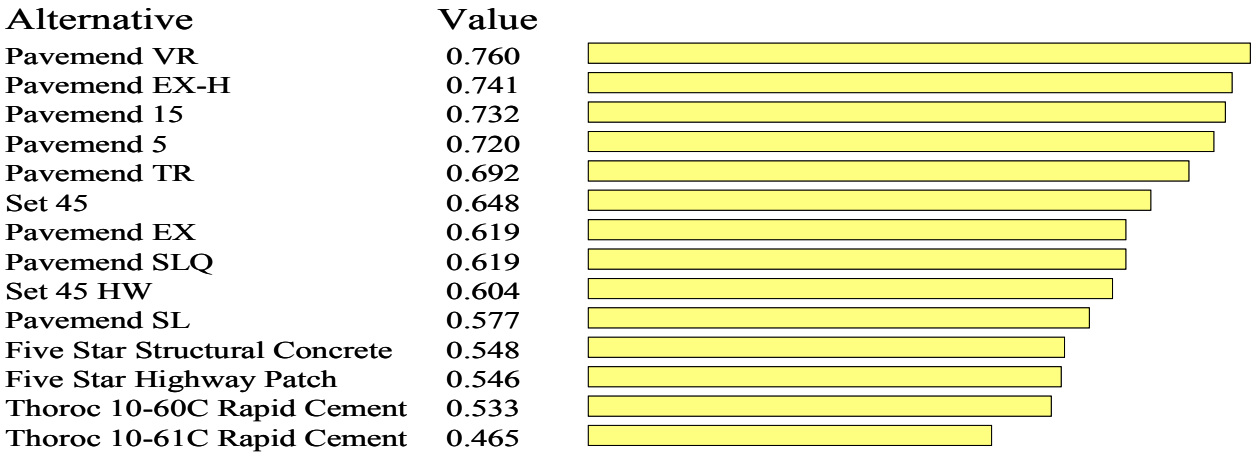


Figure 36. Ranking of Alternatives using Contingency Weighting

Further insight can be achieved by looking at a color-coded stacked bar ranking, detailing the scores on the decision maker's fundamental objectives, as seen in Figure 37. Thoroc 10-60C moves down to the second from last position. Whereas it scored #10 out of 14 under

conventional weighting, it moves down three spots since it no longer receives as much value for cost, since direct cost under contingency weighting is zero.

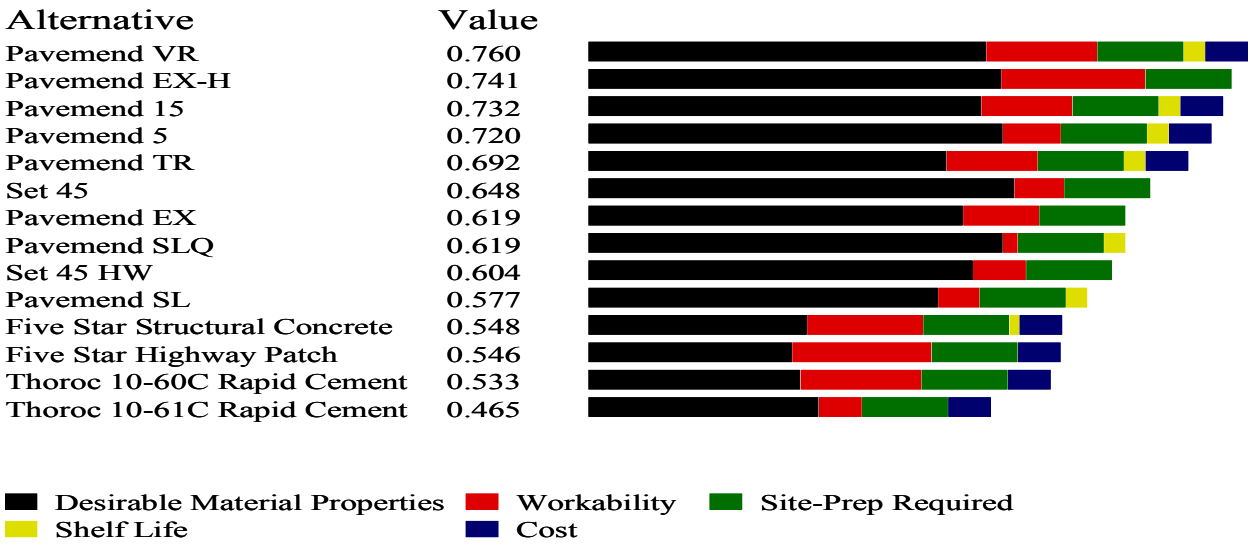


Figure 37. Alternative Ranking with Respect to Fundamental Objectives (Contingency Weighting)

Figure 38 shows the rankings with respect to individual evaluation measures using weights for a contingency repair scenario. Assuming a contingency repair scenario, the decision makers placed greater importance and thus higher weights on Early Strength. Pavemend VR surpasses Pavemend EX-H with a better score on compressive strength at three hours (ASTM C 39).

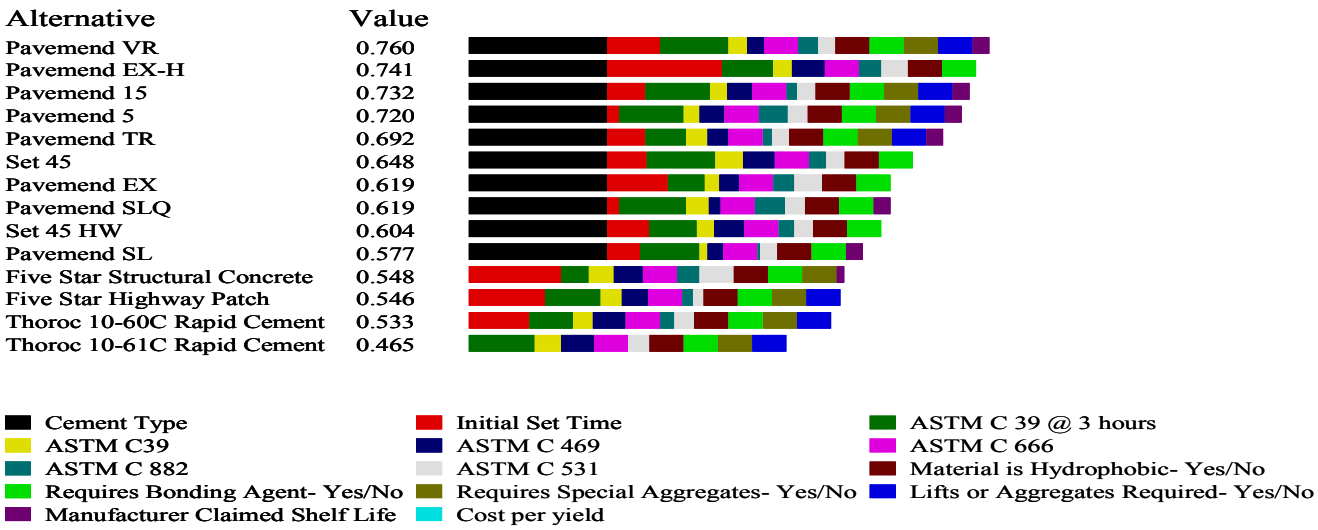


Figure 38. Alternative Ranking with Respect to Evaluation Measures (Contingency Weighting)

4.4 Sensitivity Analysis

The purpose of sensitivity analysis is to determine how changes in the model assumptions impact the alternative rankings. Since weights reflect the relative importance that is attached to changes in the evaluation measures, this can be a source of disagreement among various stakeholders for a particular decision (Kirkwood, 1997:82). Sensitivity analysis was performed with the weights previously assigned by the decision makers to determine how the rankings may change if another decision maker assigns weights differently. Sensitivity analysis also ensures that the hierarchy has been properly weighted and accurately depicts the decision maker's preferences. For the purpose of this model, sensitivity analysis was performed using the decision maker's weights for a conventional repair scenario.

The Logical Decisions® software program was used to graph sensitivity plots for measures and values in the hierarchy. Logical Decisions® shows sensitivity plots with the

assumption that as the weight for a goal or measure moves in the positive or negative direction, all other values lose or gain a percentage of their original weight. For example, if the weight on the cost goal increased by *x* percent, Logical Decisions® assumed that the remaining goals each lost the same percentage *y* that keeps the sum of the weights equal to one.

4.4.1 Sensitivity on Fundamental Objectives

Figure 39 shows the sensitivity analysis for variations in the weight on the Tier 1 value of cost. The vertical line in the graph shows the user how alternatives ranked with the current weight assignment of 0.15. Alternative rank changes are found by looking at the intersections of the lines on the plot. The user can determine where rank changes occur by visualizing right or left movement of the vertical line; the alternative that intersects the vertical line at the highest point is the best alternative for a given weight. The points at which lines cross are the weights at which two alternatives scored exactly the same.

Looking at the plot in this manner, Pavemend EX-H remains the dominant alternative for all cost weights below 0.16. Beyond this point, Pavemend VR becomes dominant until a weight of 0.39. Thoroc 10-60C Rapid Cement becomes the dominant alternative for all weights above 0.39. This shows that the weight assigned to Cost is highly sensitive, as there are many intersections (rank changes) around the current weight of 0.15.

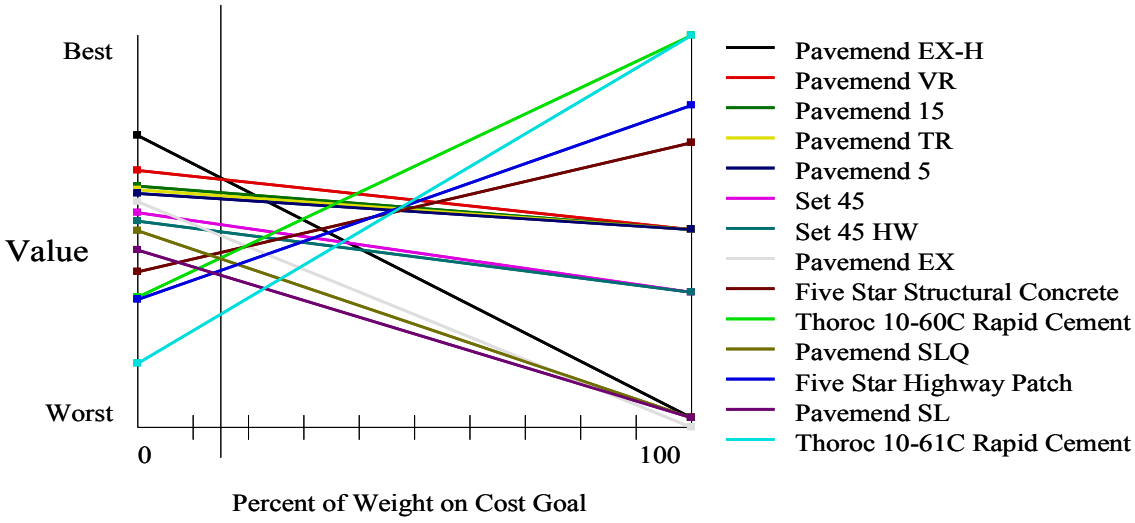


Figure 39. Sensitivity Analysis on Cost Value

Figure 40 shows the sensitivity analysis for variation in weight on the Desirable Material Properties value. The current weight assignment for this value is 0.45. Pavemend EX-H remains the dominant alternative for all weights above 0.42. The rank is very sensitive in the negative direction; Pavemend VR becomes the top alternative with a slight weight change to 0.42. It remains dominant from 0.42 to 0.14. Below 0.14, Five Star Higway Patch is the best alternative.

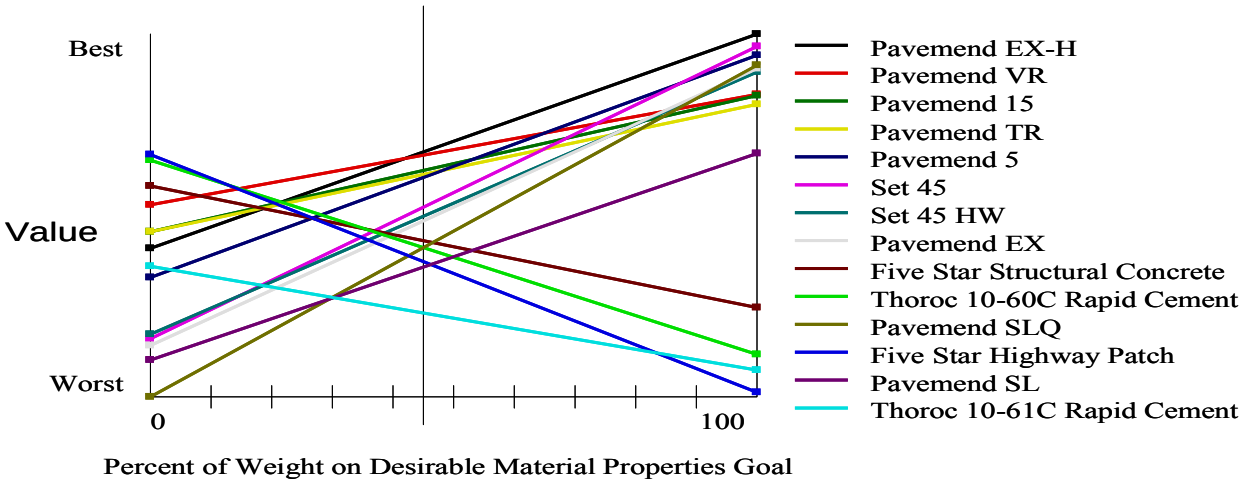


Figure 40. Sensitivity Analysis on Desirable Material Properties Value

Figure 41 shows the sensitivity analysis for variation in weight on the Shelf Life value. The current weight on Shelf Life is 0.05. Because Pavemend EX-H has a zero score for shelf life, it quickly falls out of favor as the weight on shelf life increases. Pavemend VR becomes the dominant alternative for a slight weight change to 0.06, and remains dominant for all weights greater than 0.06.

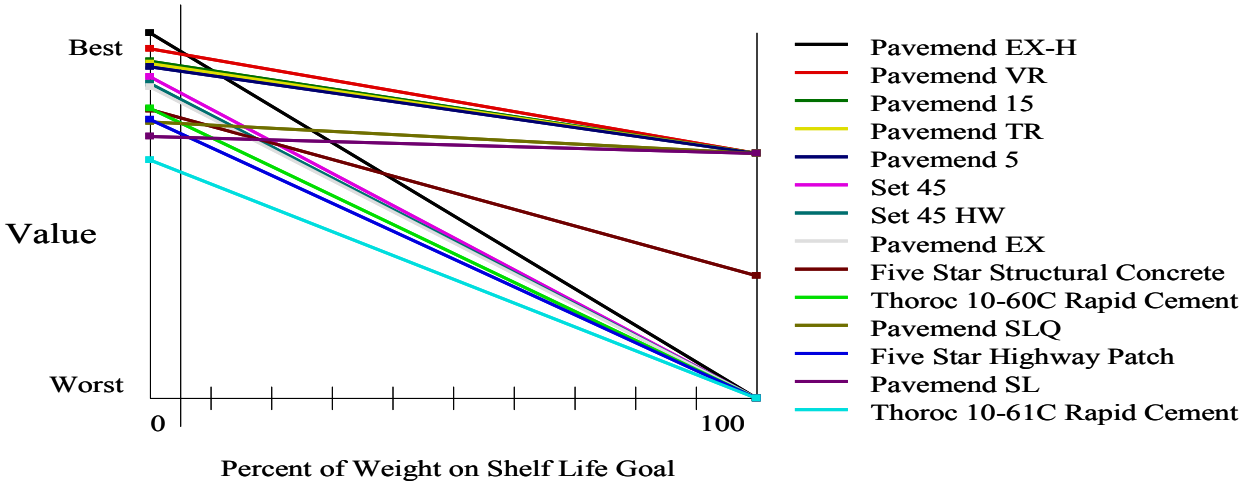


Figure 41. Sensitivity Analysis on Shelf Life Value

Figure 42 shows the sensitivity analysis on Site Preparation Required. The current weight for this value is 0.05. Weight on this value is insensitive, since no lines cross in the graph. The measures for the lower tier values that fall under Site-Prep Required are binary measures that specify if a material is hydrophobic or requires a bonding agent. Since all alternatives scored in the model did not require a bonding agent or were hydrophobic, this value is insensitive to its weight.

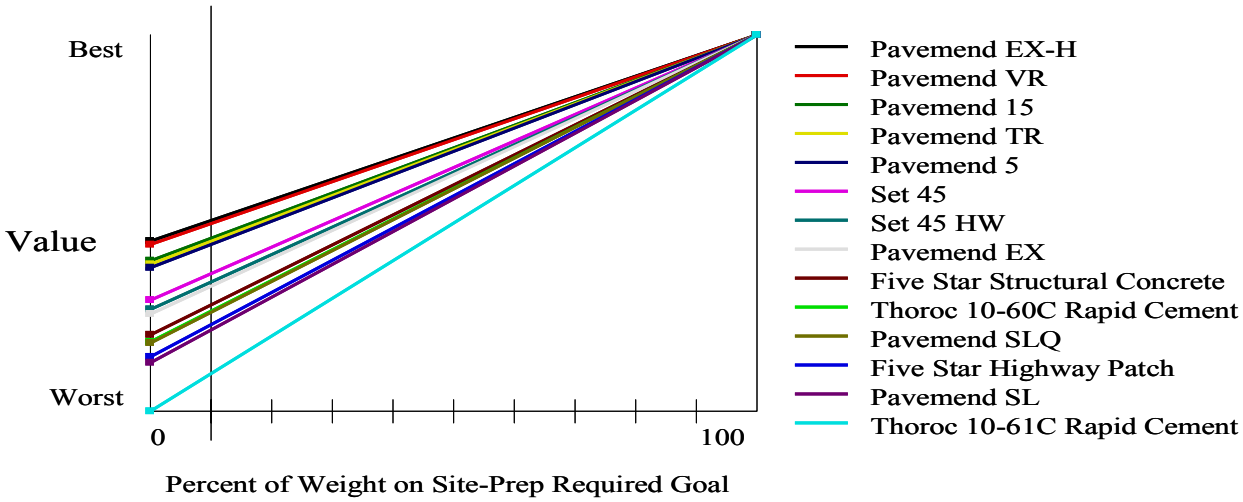


Figure 42. Sensitivity Analysis on Site-Preparation Required Value

Figure 43 shows the sensitivity analysis on Workability. The current global weight is 0.25. A small weight change in the negative direction to 0.23 causes Pavemend VR to be the top choice. Pavemend VR is the dominant alternative for weights ranging from 0.14 to 0.23. For weights below 0.14, Pavemend 5 is the best alternative. This value is highly sensitive to weight, causing three alternatives to rank at the top for only a 0.09 swing in weight.

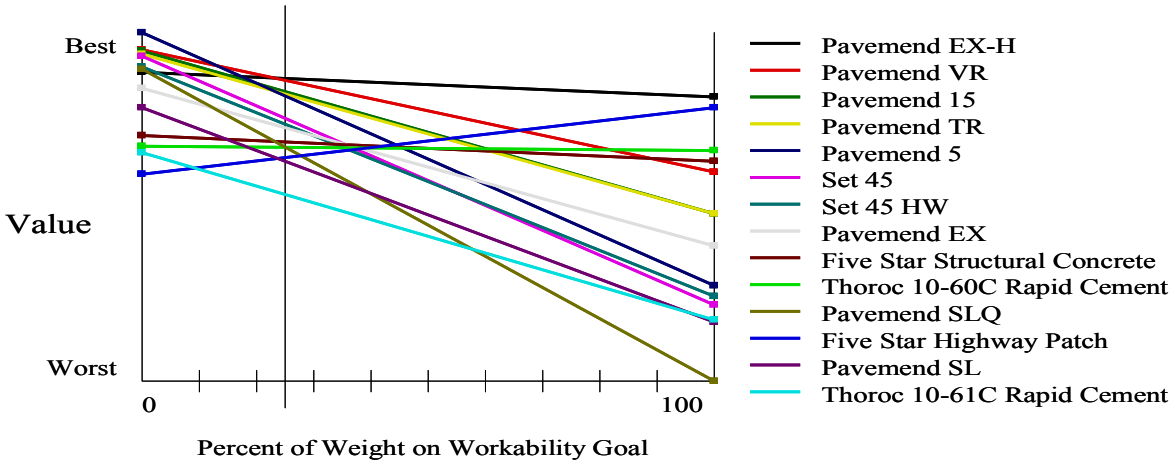


Figure 43. Senstivity Analysis on Workability Value

4.5 Summary of Results and Analysis

Although Pavemend EX-H is the best alternative under the current weighting, sensitivity analysis reveals that Pavemend VR becomes the best alternative with only slight changes in weights on four of the five fundamental objectives. Clearly, the decision of which of these materials is best is highly dependent on the weights assigned by the decision maker. For this reason, consideration should be given to both alternatives for purposes of field testing and operational use. Pavemend VR is better suited to repairs in a contingency repair scenario because it doesn't require addition of aggregates, and has a higher early strength. This would make it faster to place, and its higher early strength is preferable when the repair must be ready for traffic within hours after placement.

Table 8 is a summary of weight sensitivity for all values and measures. The Sensitive Weight Range column lists the weight ranges that cause a new alternative (shown in parentheses) to become dominant. The Insensitive Weight Range column lists the weight ranges for which the best alternative, Pavemend EX-H, remains dominant.

Table 8. Summary of Weight Sensitivity on Values

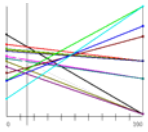
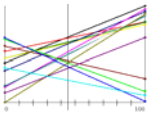
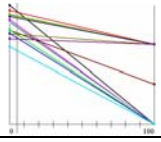
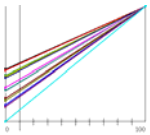
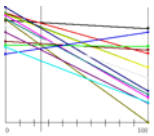
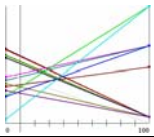
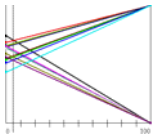
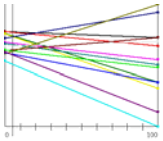
Value	Sensitivity Graph	Current Global Weight	Sensitive Weight Range	Insensitive Weight Range
Cost		0.15	0.16-0.39 (Pavemend VR), 0.39-1.0 (Thoroc 10-60c)	0-0.16
Desirable Material Properties		0.45	0.15-0.42 (Pavemend VR), 0-0.15 (Five Star Highway Patch)	0.42-1.00
Shelf Life		0.05	.06-1.00 (Pavemend VR)	0-.06
Site-Prep Required		0.1	N/A	0.00-1.00
Workability		0.25	0.12-0.22 (Pavemend VR), 0-0.12 (Pavemend 5)	.22-1.00
Direct Cost		0.1	0.26-0.32 (Set 45), 0.32-1.0 (Thoroc 10-60c)	0-0.26
Specialized Aggregate Required		0.05	.06-1.0 (Pavemend VR)	0-.06
Bond to Existing Substrate		0.05	0.23-0.65 (Pavemend 5), 0.23-1.0 (Pavemend SLQ)	0-0.23

Table 8 (Continued)

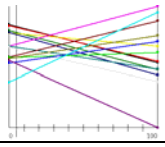
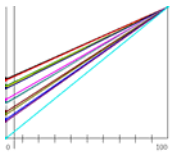
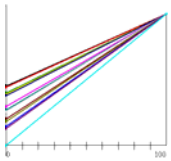
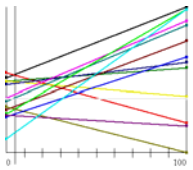
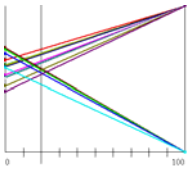
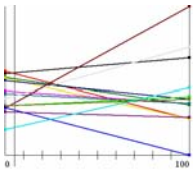
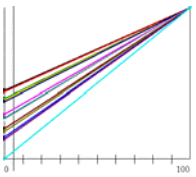
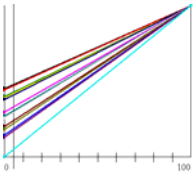
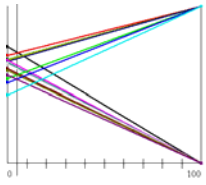
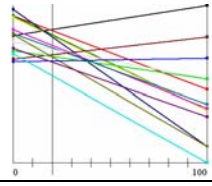
Value	Sensitivity Graph	Current Global Weight	Sensitive Weight Range	Insensitive Weight Range
Compressive Strength		0.05	0.27-1.0 (Set 45)	0-0.27
Durability		0.05	N/A	0-1.0
Early Strength		0	N/A	0-1.0
Modulus of Elasticity		0.05	0-0.04 (Pavemend VR)	0.04-1.0
Restrained Drying Shrinkage		0.2	0-.07 (Five Star Structural Concrete)	0.07-1.0
Thermal Expansion		0.05	0-0.03 (Pavemend VR), 0.40-1.0 (Five Star Structural Concrete)	0.03-0.40
Bonding Agent Required?		0.05	N/A	0-1.0
Hydrophobic?		0.05	N/A	0.1.0

Table 8 (Continued)

Value	Sensitivity Graph	Current Global Weight	Sensitive Weight Range	Insensitive Weight Range
Aggregate/Lift Requirement		0.05	0.06-1.0 (Pavemend VR)	0-0.06
Working Time		0.2	0-0.09 (Pavemend 5), 0.09-0.19 (Pavemend VR)	0.19-1.0

V. Summary and Conclusions

5.1 Overview

The purpose of this research was to provide a tool for military engineers to best select a repair material for partial depth repairs of concrete airfield pavements. As new materials are developed by the private sector, this research will also assist civil engineers with ranking the new alternatives. Materials that favor well in this model can be chosen for additional laboratory and field testing, and those that do not are easily eliminated from consideration. The approach chosen was a multi-criteria decision making tool known as value-focused thinking. The final step in Shoviak's 10 step VFT process is to make conclusions and recommendations. This section summarizes the research questions presented in Chapter 1, discusses the benefits and limitations of the value model, describes possibilities for future research, and makes final conclusions.

5.2 Research Summary

In Chapter 1, several research questions were identified regarding the selection of airfield rigid pavement repair materials. These questions are summarized in Table 9 below.

Table 9. Summary of Research Questions

Research Questions	
1	What are the characteristics that engineers look for in an ideal repair material?
2	What characteristics and properties are uniquely important to military engineers in the repair of airfield pavements?
3	What is the appropriate methodology for choosing the best pavement repair material?
4	What are the available materials suitable for concrete spall repair?
5	Which material(s) should engineers select for concrete pavement spall repair?

What are the characteristics that engineers look for in an ideal repair material?

Engineers look for a material with favorable physical properties needed to produce a long lasting repair. The material should have low drying shrinkage, high bond strength, and high compressive strength. It should be durable and able to withstand weather conditions such as freeze/thaw cycles. It should also be dimensionally compatible with the underlying substrate. This means that it should have a similar modulus of elasticity and coefficient of thermal expansion to the existing pavement. If a material meets the above criteria, it has a high chance of providing a long service life without early failure.

What characteristics and properties are uniquely important to military engineers in the repair of airfield pavements?

Military engineers look for a material that is low in cost, has favorable physical properties, with a long shelf life and that is easy to prepare and place. The material should be low in cost so that it does not strain financial resources, and unnecessarily waste taxpayer dollars, when a cheaper alternative may perform equally well. Military engineers need a material that will withstand heavy aircraft traffic; the material should have adequate physical properties to withstand these loads and avoid additional maintenance due to early failure. In order to avoid improperly placed repairs, a material is needed that is easy to prepare and place. The material should have high workability and require minimal repair site preparation.

What is the appropriate methodology for choosing the best pavement repair material?

Value-Focused Thinking was determined to be the best methodology to select pavement repair materials. VFT is an appropriate methodology to use when there are competing objectives

in a decision. It is an objective tool that can balance all values a decision maker faces when selecting and ideal pavement repair material. The VFT process has the added benefit in that it sometimes leads the decision maker to think of possible alternatives that were previously unconsidered.

What are the available materials suitable for concrete spall repair?

The materials that were found to be suitable for concrete spall repair include products on the commercial market advertised for structural concrete repair applications. There are too many products on the market to list, however, so the decision makers chose materials for this model with good industry reputation, and properties that were favorable for good results.

Which material(s) should engineers select for concrete pavement spall repair?

This model found Pavemend VR, made by Ceratech Inc., to be the best candidate for partial depth spall repair. The material scored well on all measures in the hierarchy, and warrants field testing and possible use on operational airfields. In addition, four other Ceratech products scored high in this model and should also be considered: Pavemend EX-H, Pavemend 15, Pavemend 5, and Pavemend TR.

5.3 Model Strengths

The value model provides a systematic, objective, and defendable method to rank repair product alternatives. The model is developed in a systematic series of steps that can be easily repeated or tailored to the needs of other stakeholders. By developing and weighting a value hierarchy before considering alternatives, the model is objective and free of bias that could

unduly influence the selection of alternatives. By numerically scoring repair material alternatives with this model, the decision of which material to select can be defended with quantifiable confidence.

5.4 Model Limitations

This model requires extensive data and lab testing of repair materials in order for materials to be scored in the model. This testing is expensive and few manufacturers perform all the tests. For this reason, many alternatives with the potential to perform well in this decision had to be omitted for lack of data. In addition, many engineers find manufacturer-reported data to be suspect and often inflated. Due to the preponderance of manufacturer data used in this model, the results assume that manufacturers are properly performing and reporting results of material property tests. As materials undergo further lab testing, manufacturer data in this model should be replaced with data from independent lab testing to ensure the integrity of data in this model.

5.5 Future Research

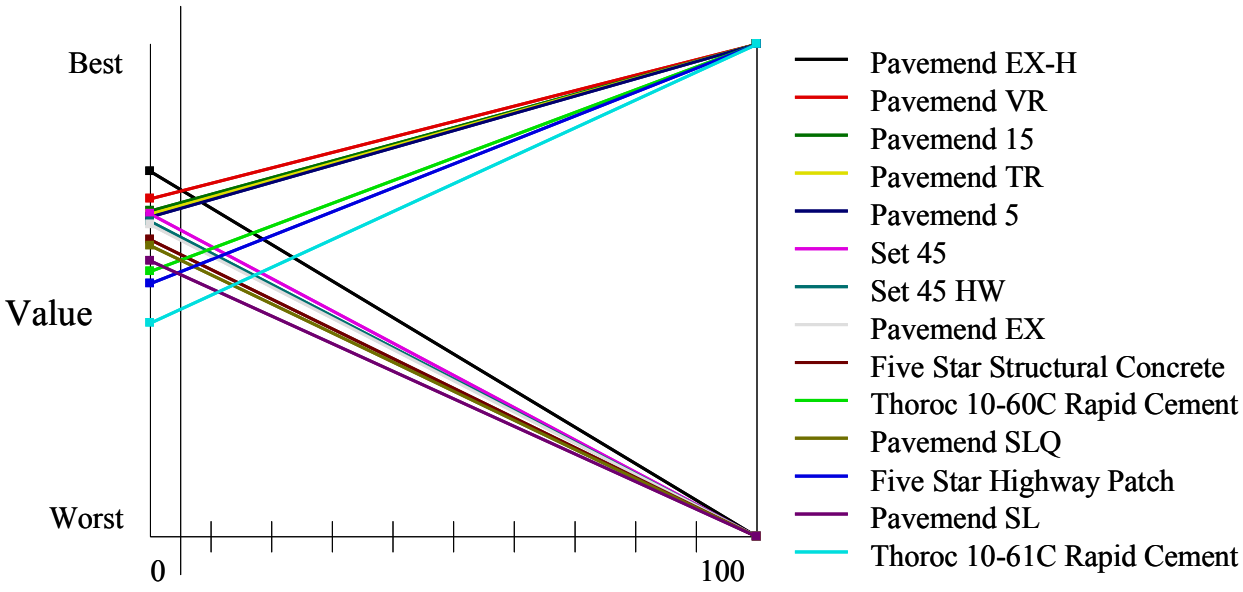
As stated earlier, much effort is needed to perform independent testing of concrete repair materials. Although this may be expensive, it is well worth the cost to ensure that expensive materials are not fielded in operational use, and found to fail early and require successive repairs. Additionally, more research is needed to correlate material properties with field performance. Although generalizations can be made regarding properties that are favorable to produce long lasting repairs, minimum acceptable standards have not been established and agreed on by researchers.

5.6 Conclusions

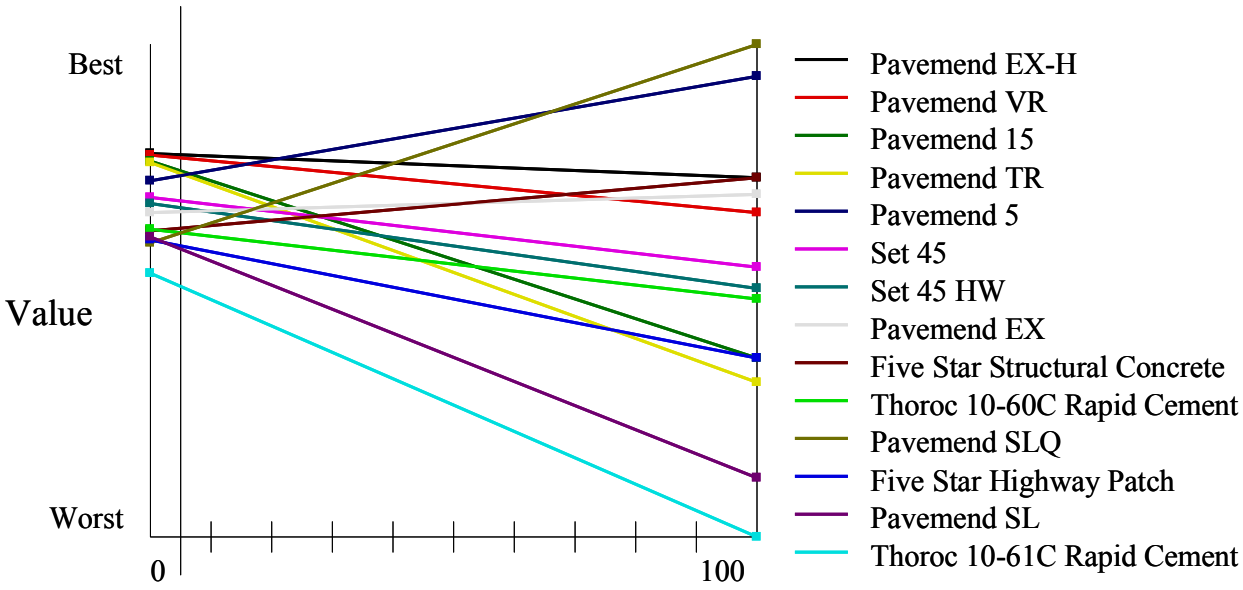
This research shows that value-focused thinking is an appropriate methodology for selecting the best material to use for partial-depth rigid pavement spall repair. This research is unique since it is the first decision tool developed that will select the best repair material in this specific context. Many engineers still regard concrete repair material selection as "more of an art than a science." This research provides the much needed science and objectivity to the material selection process.

The model indicates that Pavemend EX-H is the best alternative to use for conventional repair scenarios, and Pavemend VR is the best alternative for military engineers to use in contingency repair scenarios. This model shows that poor product candidates for pavement repair can be eliminated from consideration, avoiding the expense of testing and fielding inferior products. By implementing the decision strategy presented in this thesis, airfield pavement repairs will last longer and require less maintenance.

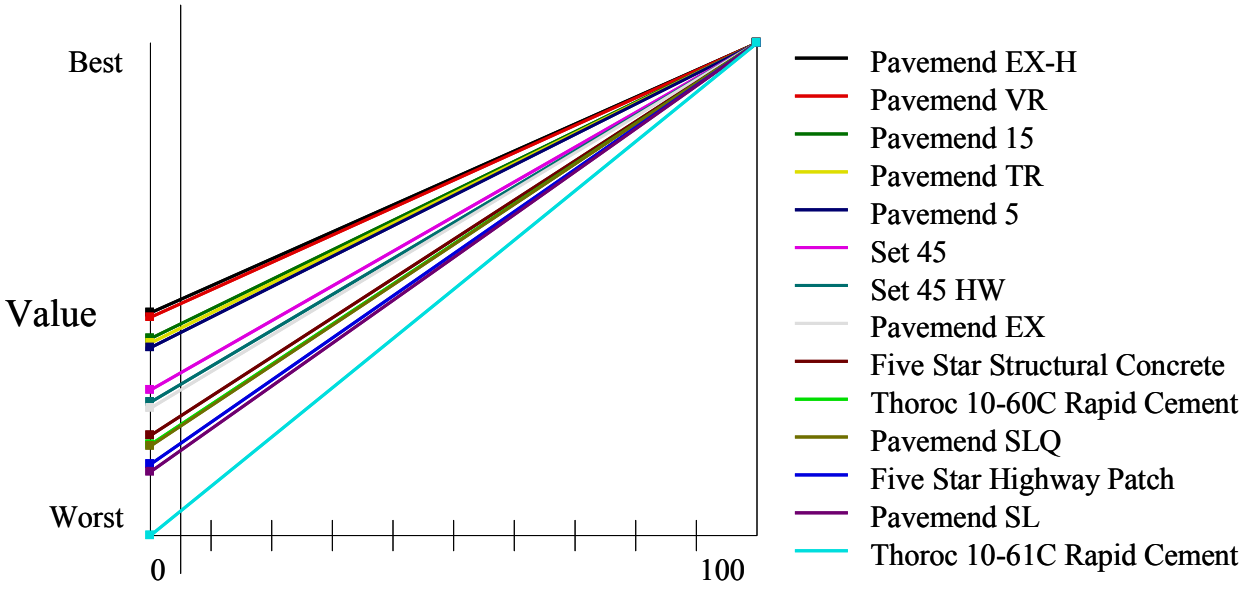
Appendix A: Sensitivity on Measures (Conventional Weighting)



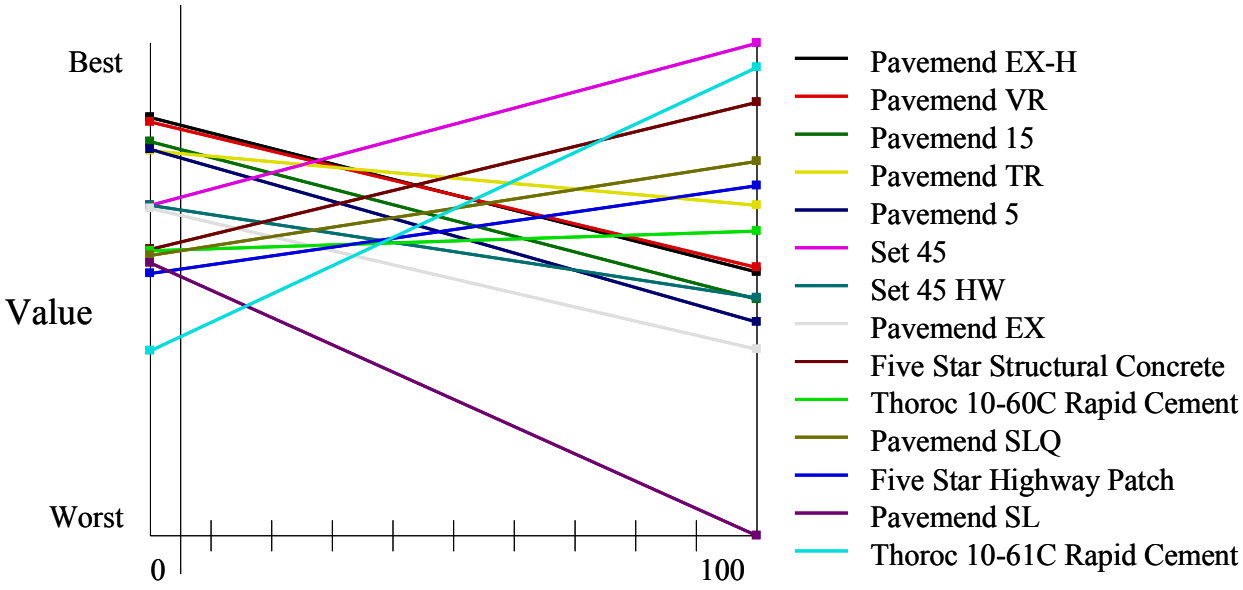
Percent of Weight on Aggregate/Lift Requirement Goal



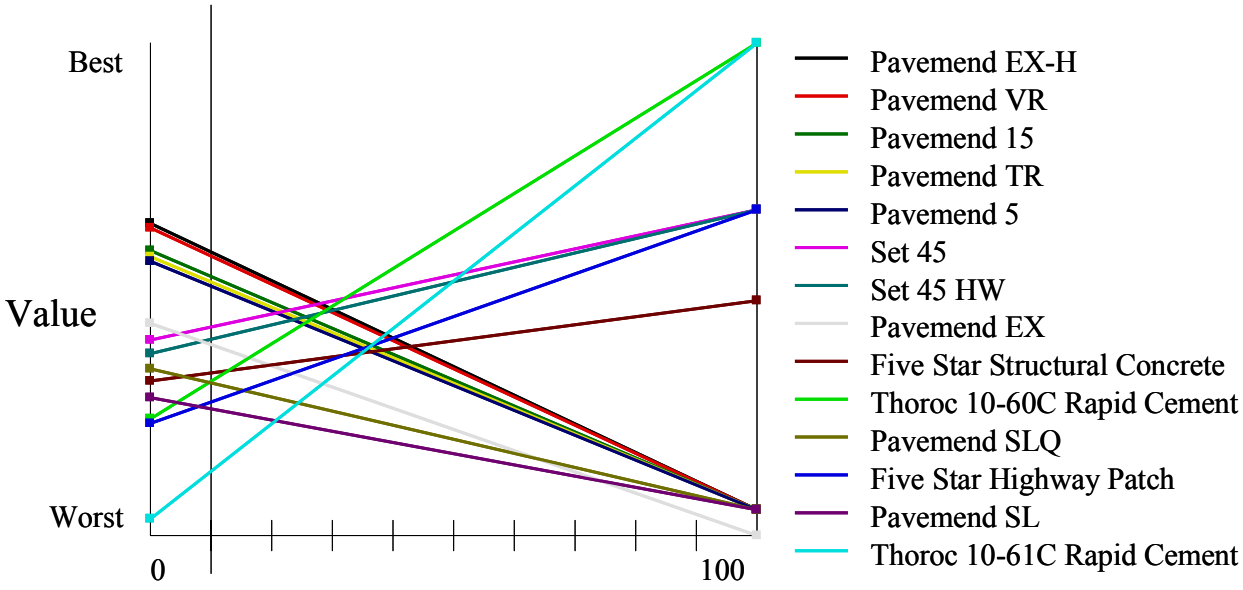
Percent of Weight on Bond to Existing Substrate Goal



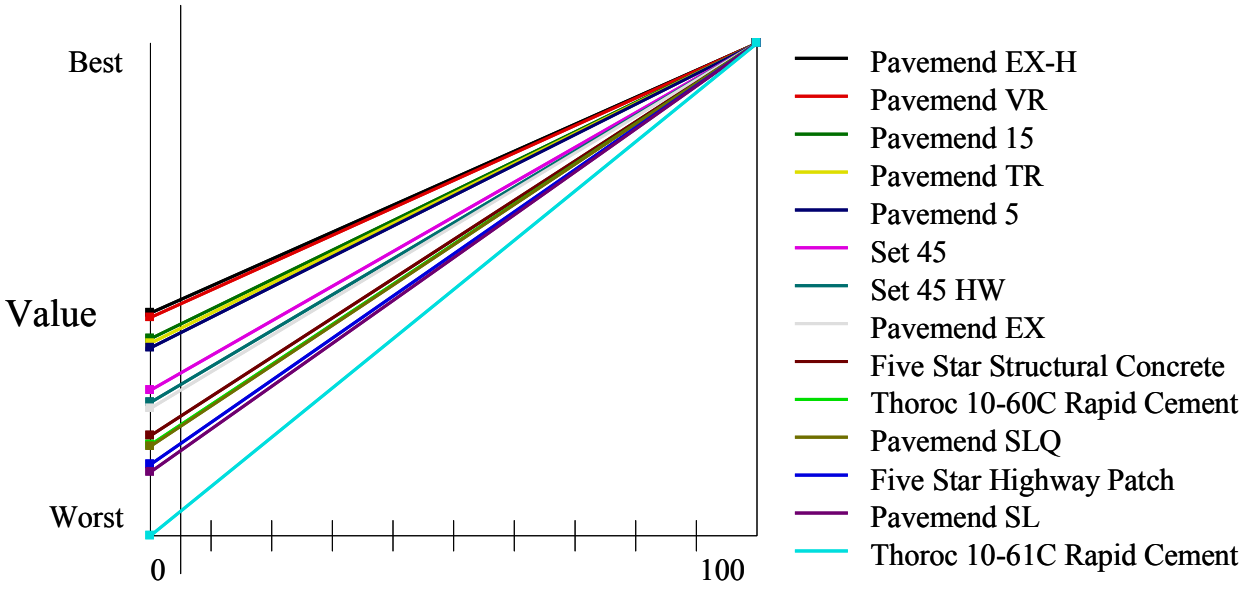
Percent of Weight on Bonding Agent Required? Goal



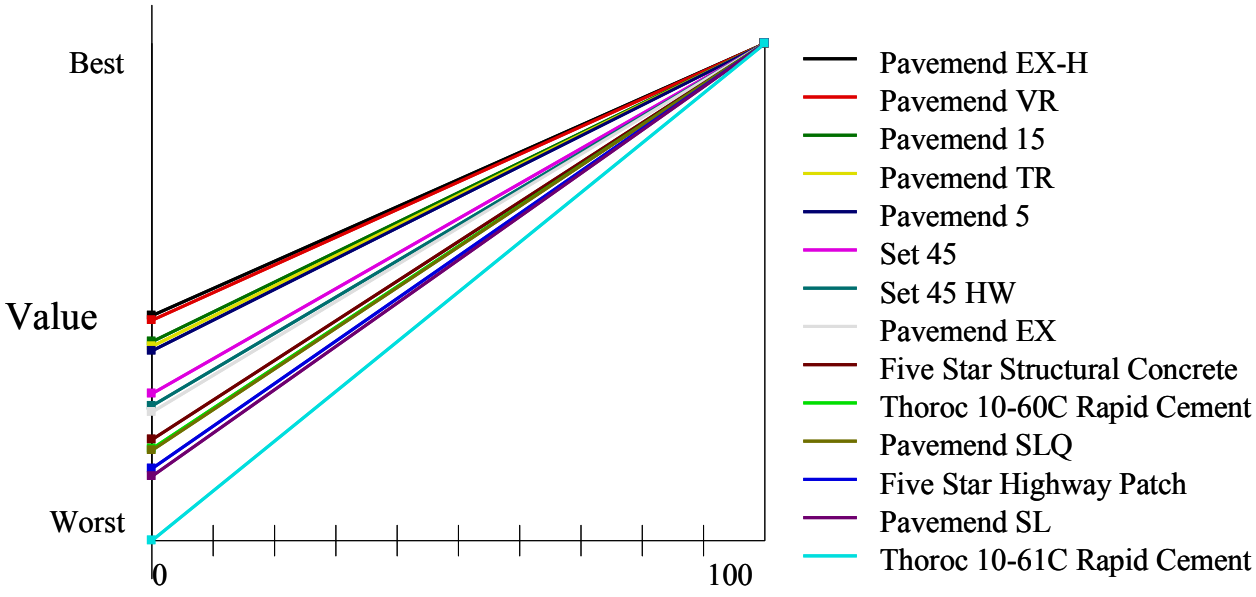
Percent of Weight on Compressive Strength Goal



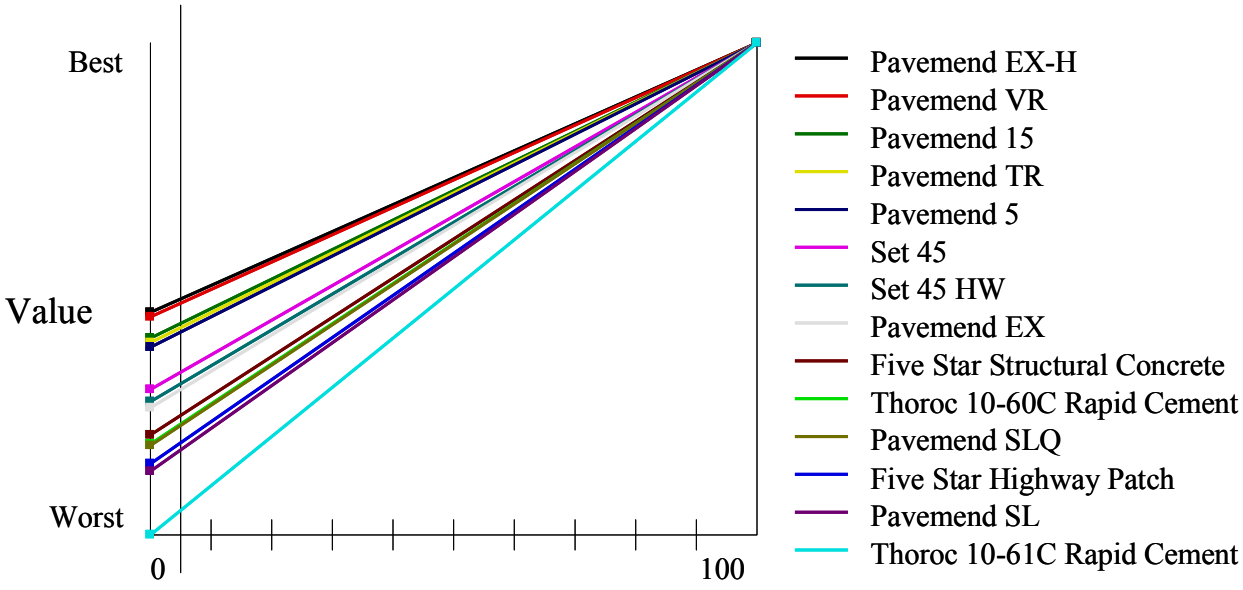
Percent of Weight on Direct Cost Goal



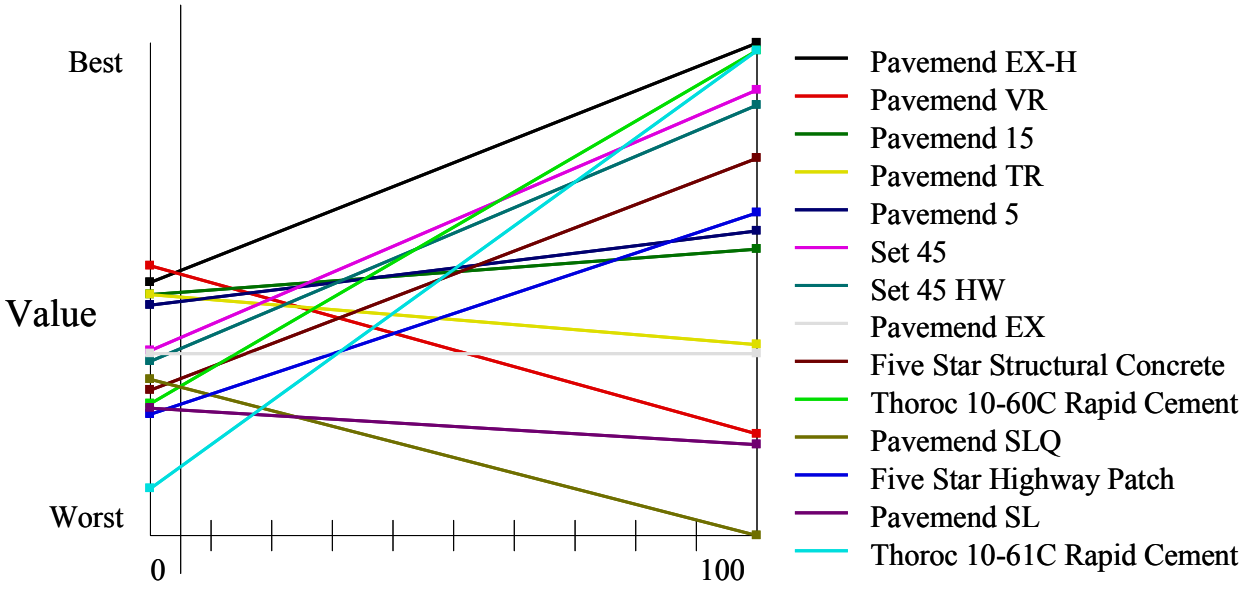
Percent of Weight on Durability Goal



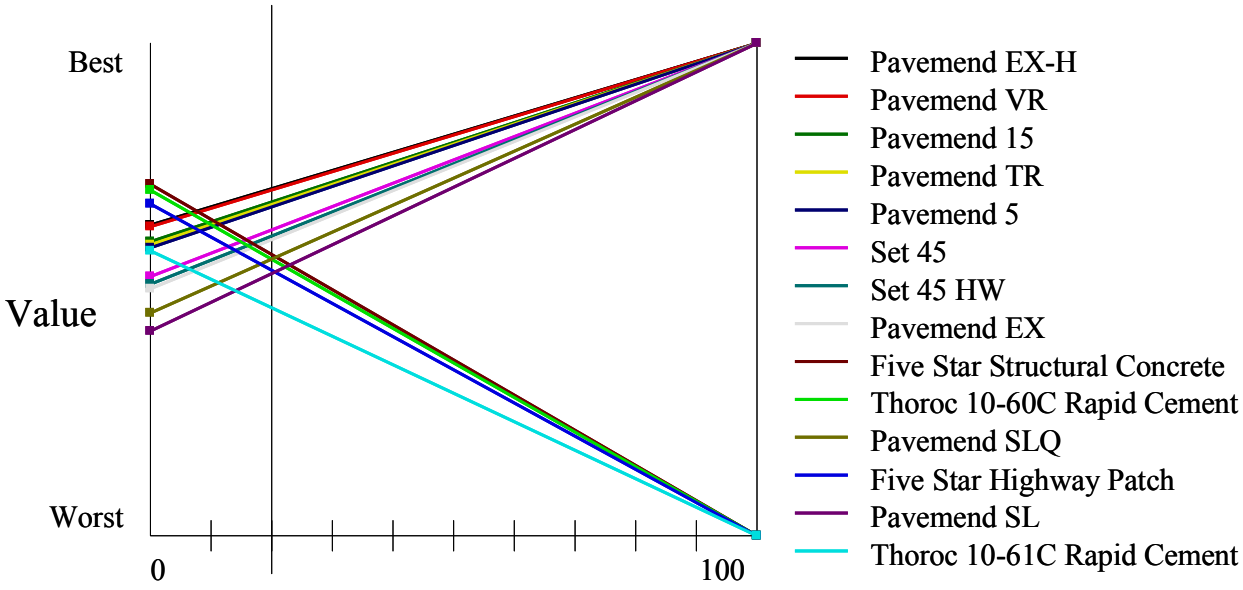
Percent of Weight on Early Strength Goal



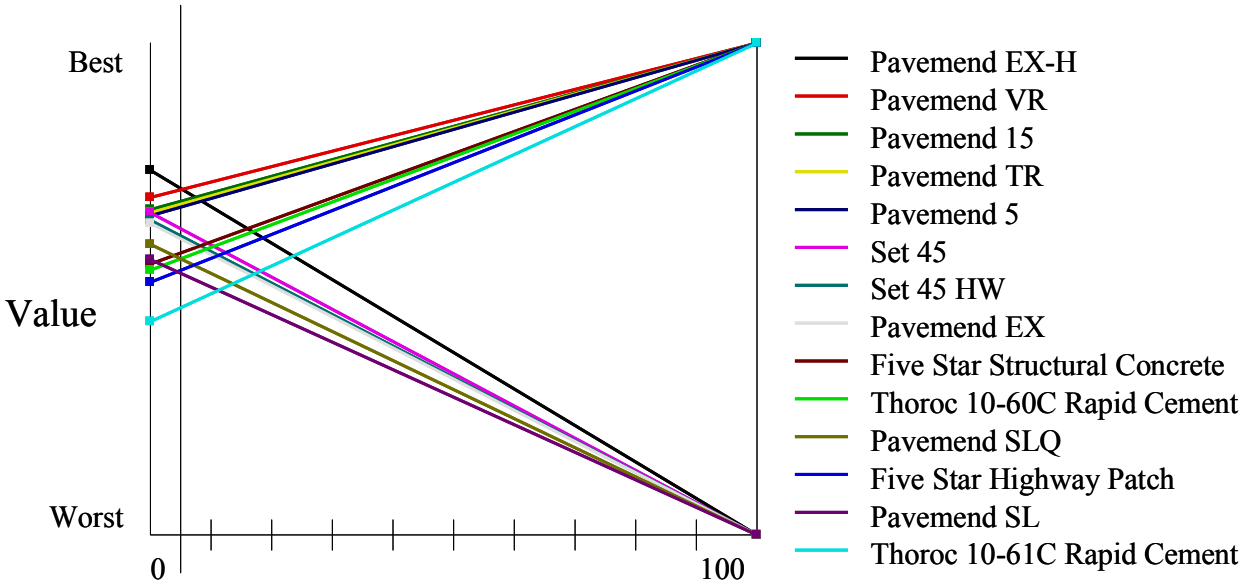
Percent of Weight on Hydrophobic? Goal



Percent of Weight on Modulus of Elasticity Goal

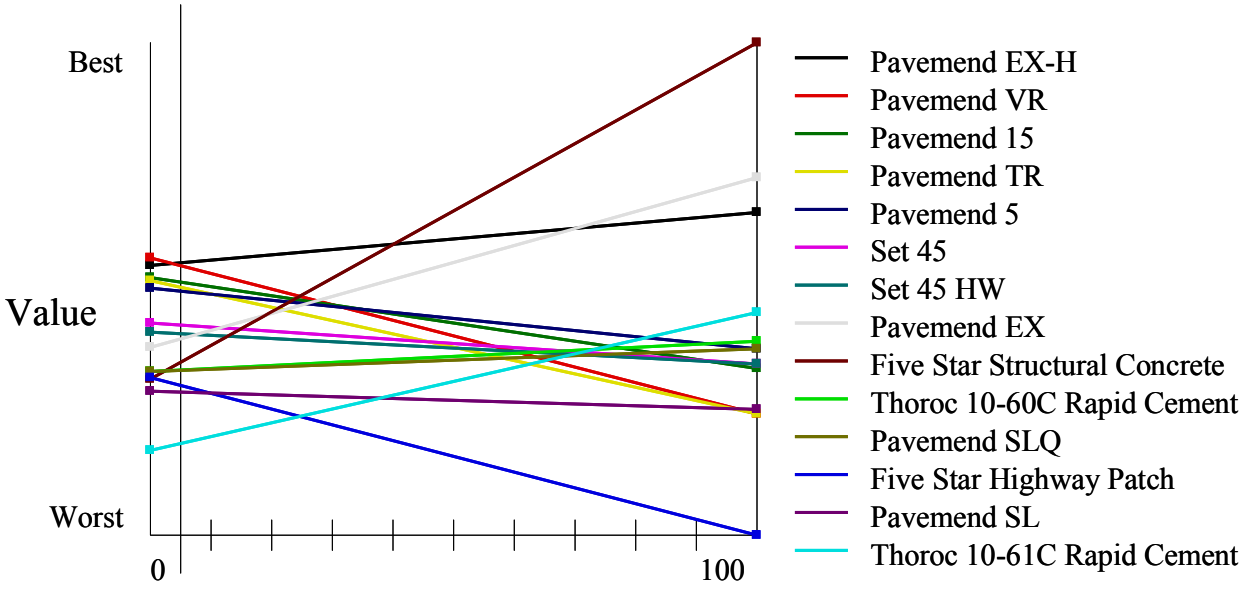


Percent of Weight on Restrained Drying Shrinkage Goal

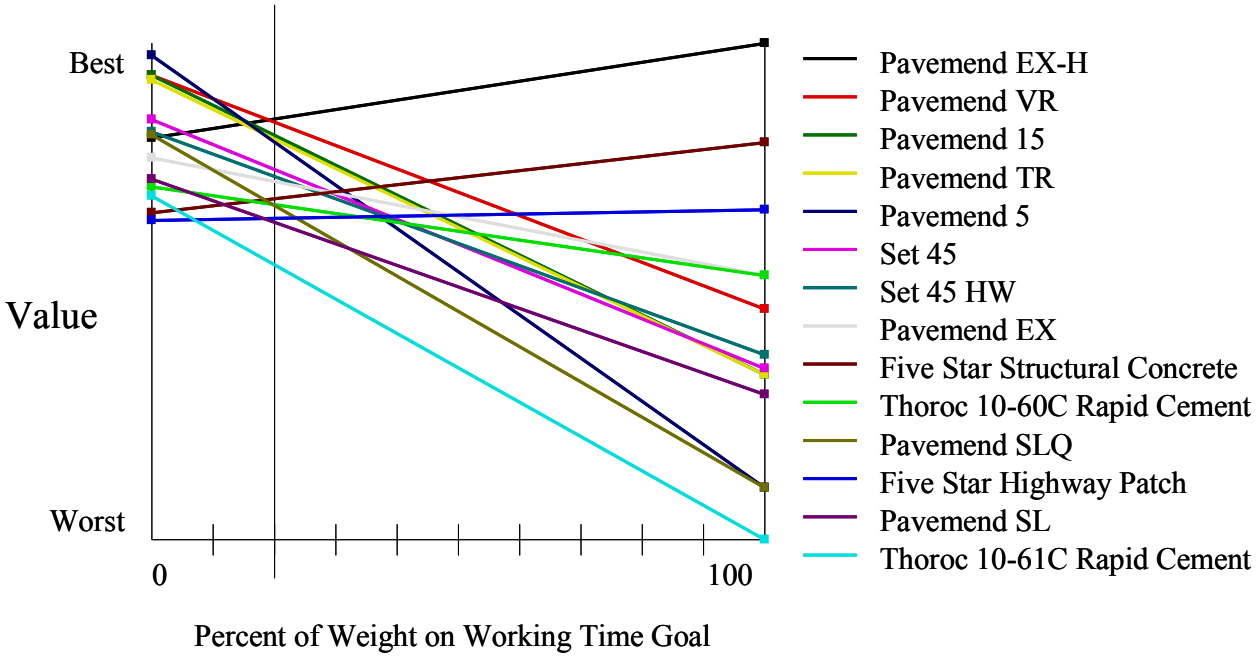


Percent of Weight on Specialized Aggregate Required Goal

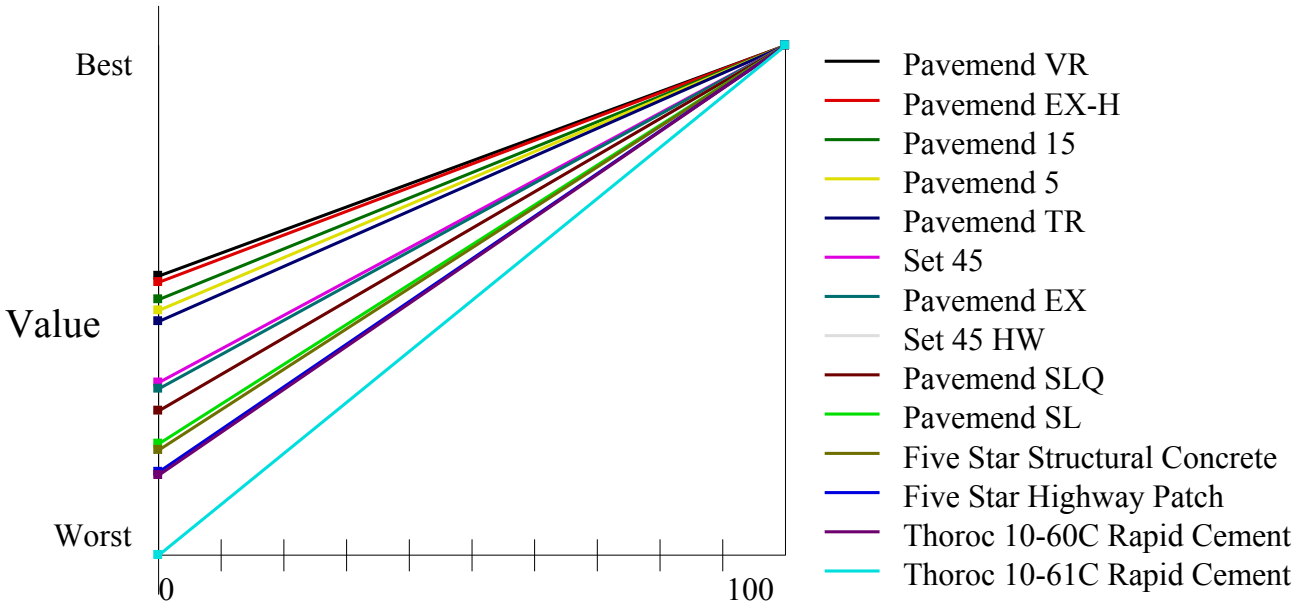
Preference Set = NEW PREF. SET



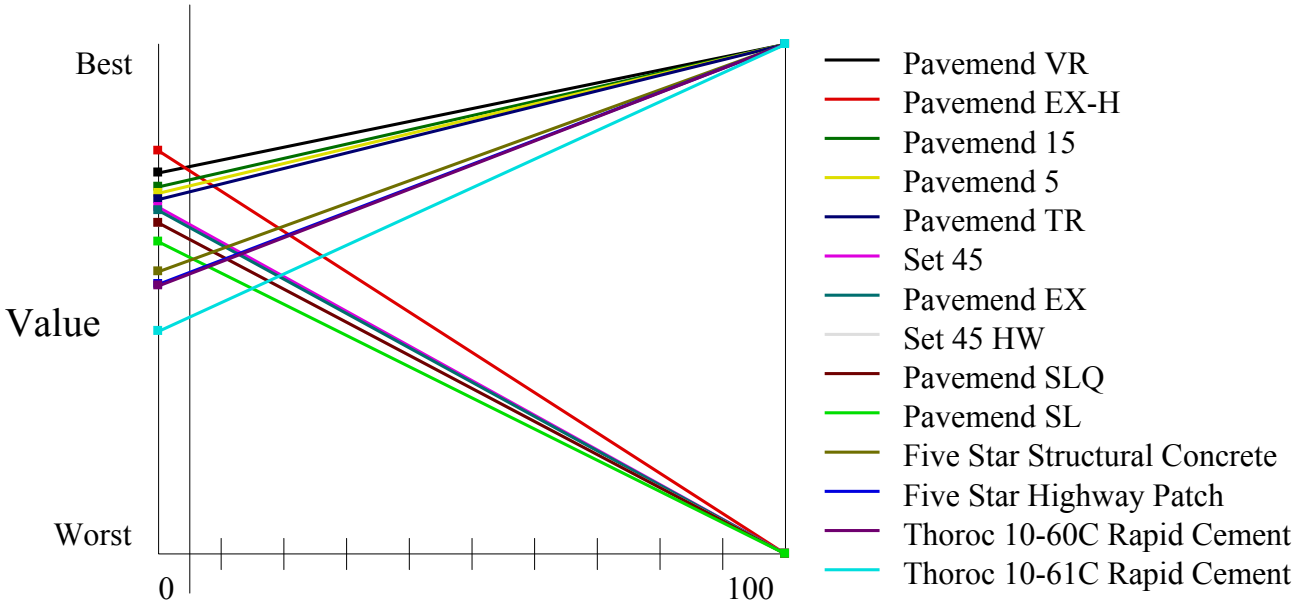
Percent of Weight on Thermal Expansion Goal


Best
Value
Worst
0
100
Percent of Weight on Working Time Goal
Pavemend EX-H
Pavemend VR
Pavemend 15
Pavemend TR
Pavemend 5
Set 45
Set 45 HW
Pavemend EX
Five Star Structural Concrete
Thoroc 10-60C Rapid Cement
Pavemend SLQ
Five Star Highway Patch
Pavemend SL
Thoroc 10-61C Rapid Cement

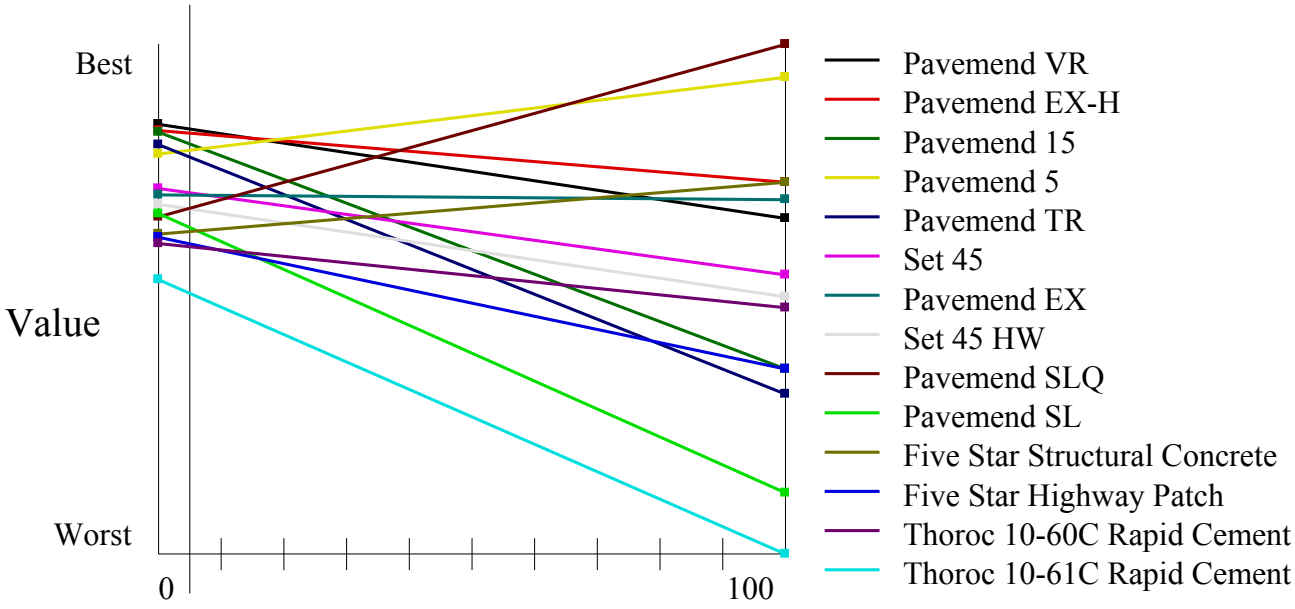
Appendix B: Sensitivity on Measures (Contingency Weighted)



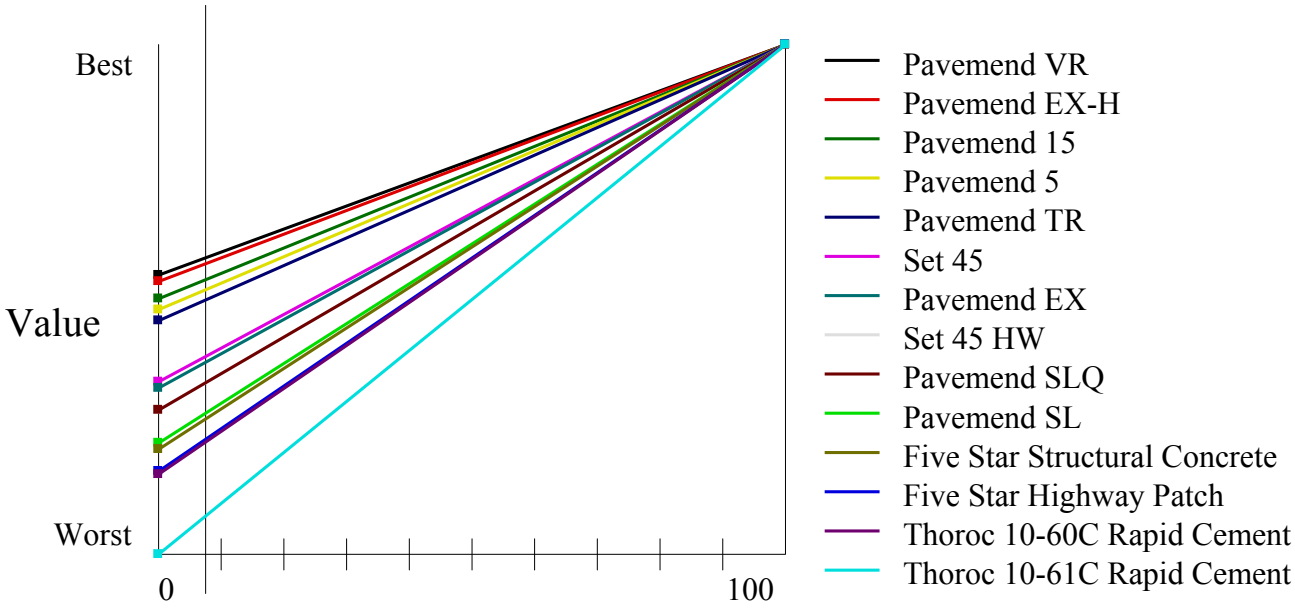
Percent of Weight on Direct Cost Goal



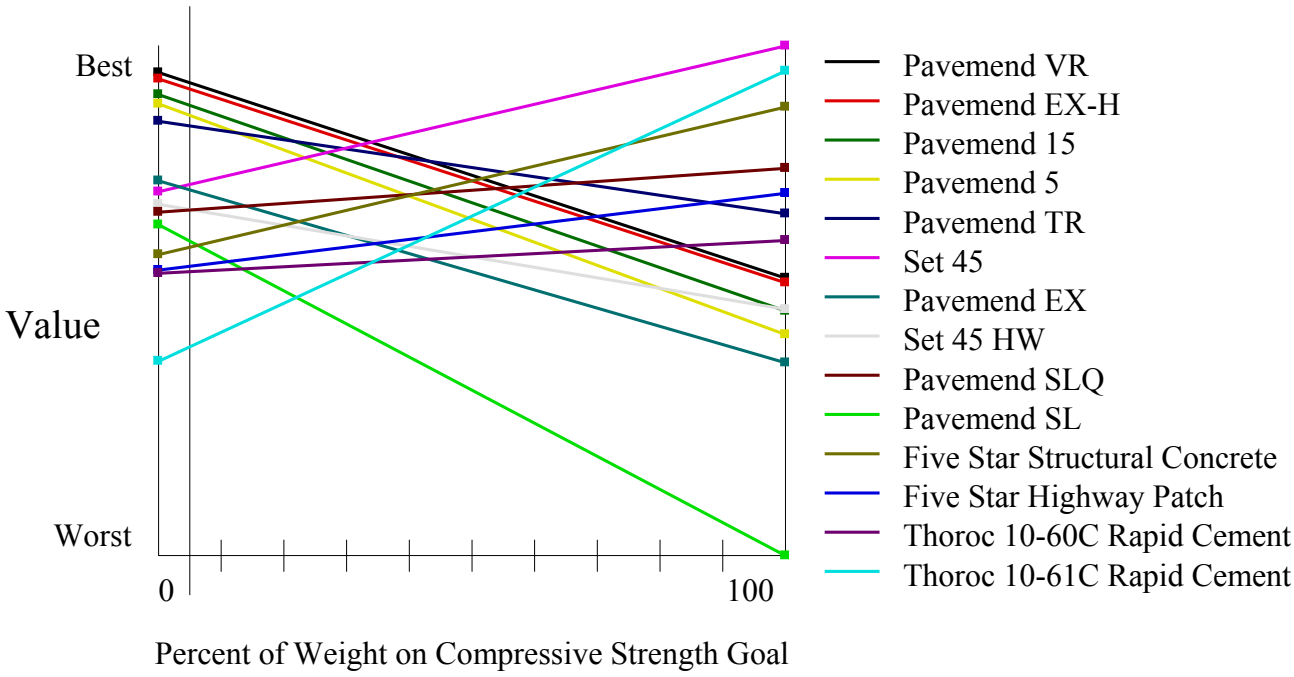
Percent of Weight on Specialized Aggregate Required Goal



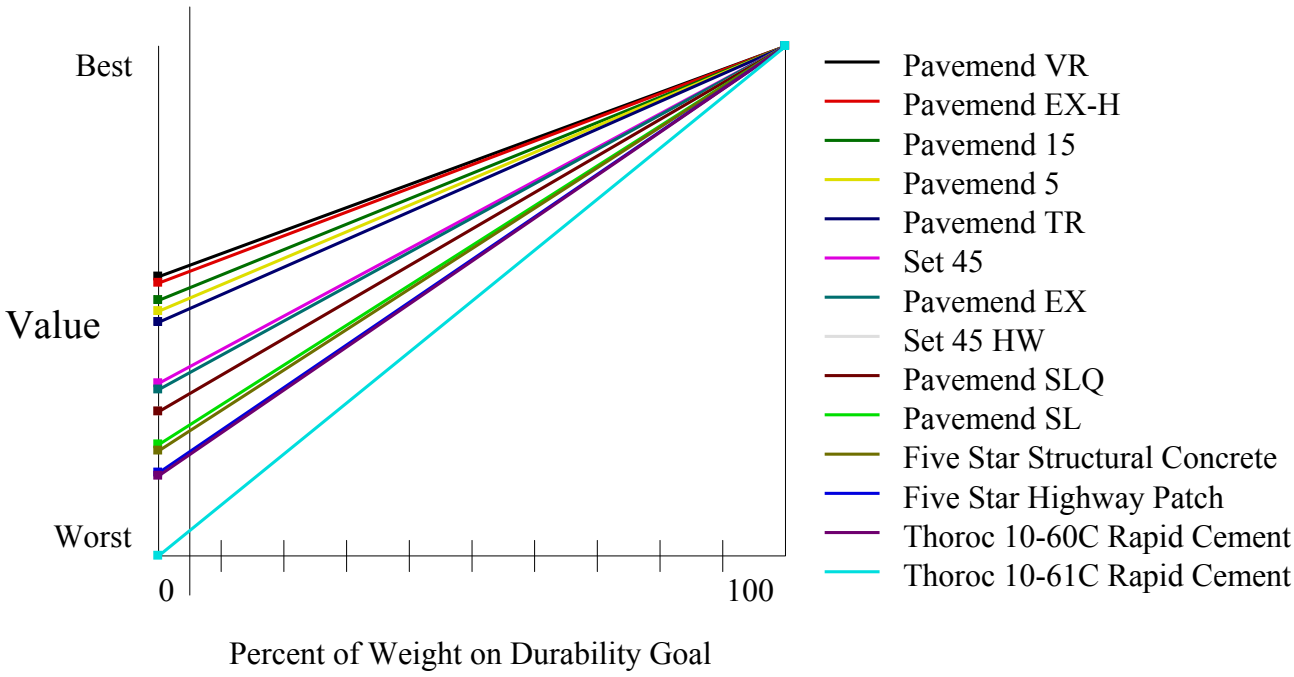
Percent of Weight on Bond to Existing Substrate Goal



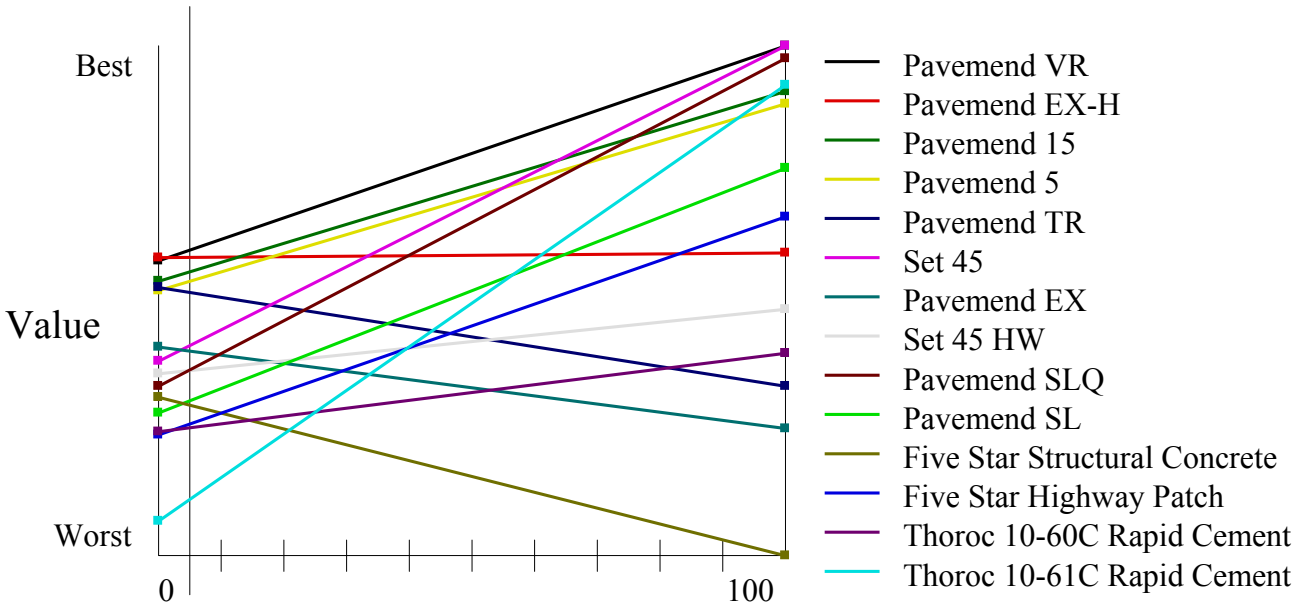
Percent of Weight on Bonding Agent Required? Goal



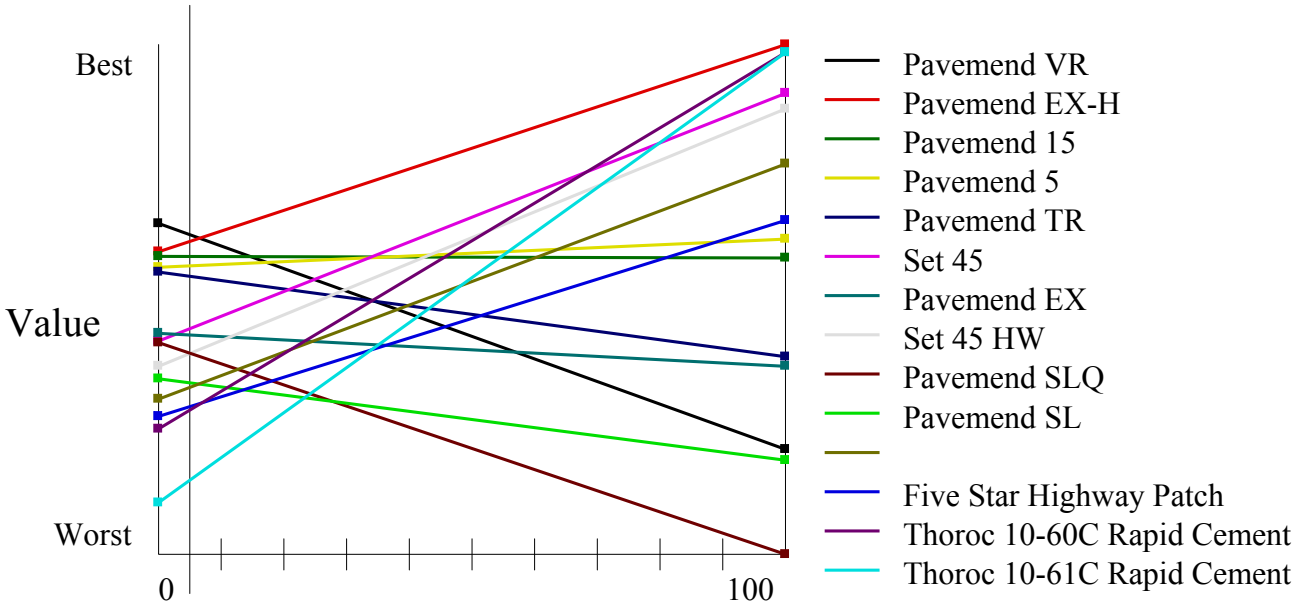
Percent of Weight on Compressive Strength Goal



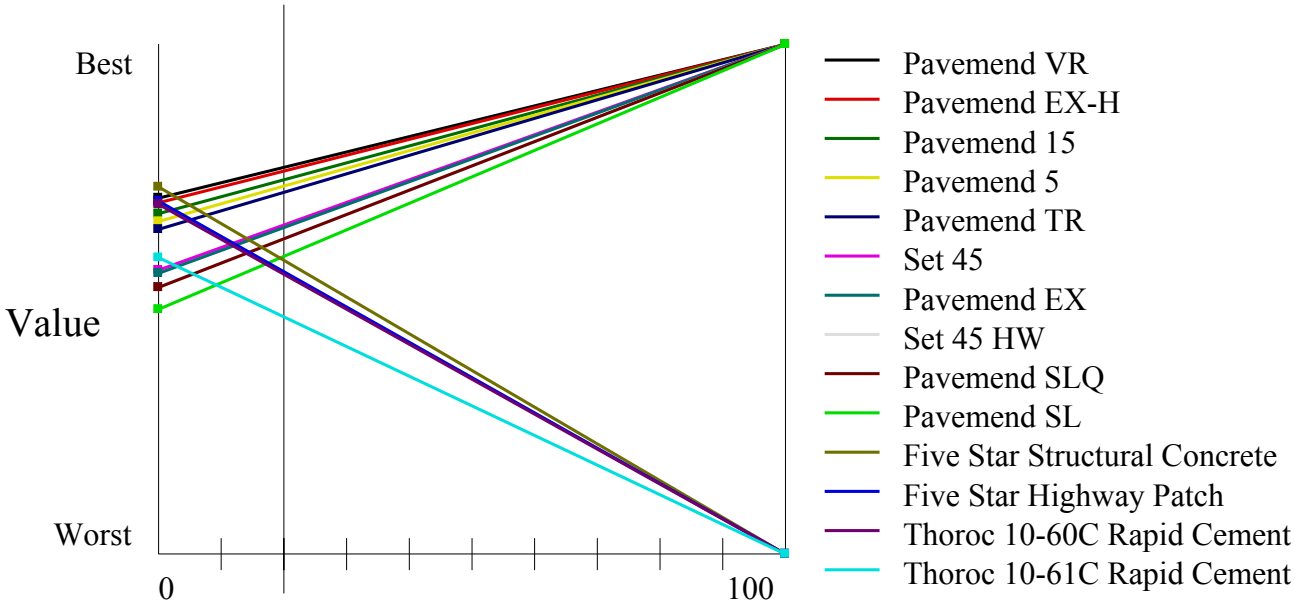
Percent of Weight on Durability Goal



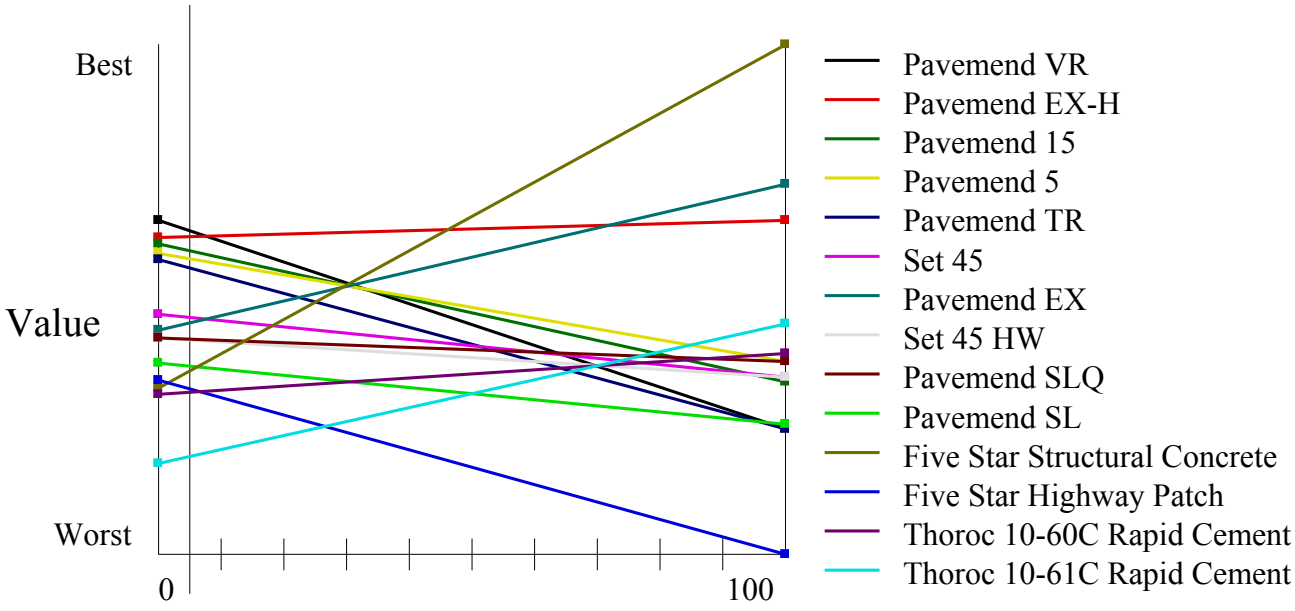
Percent of Weight on Early Strength Goal



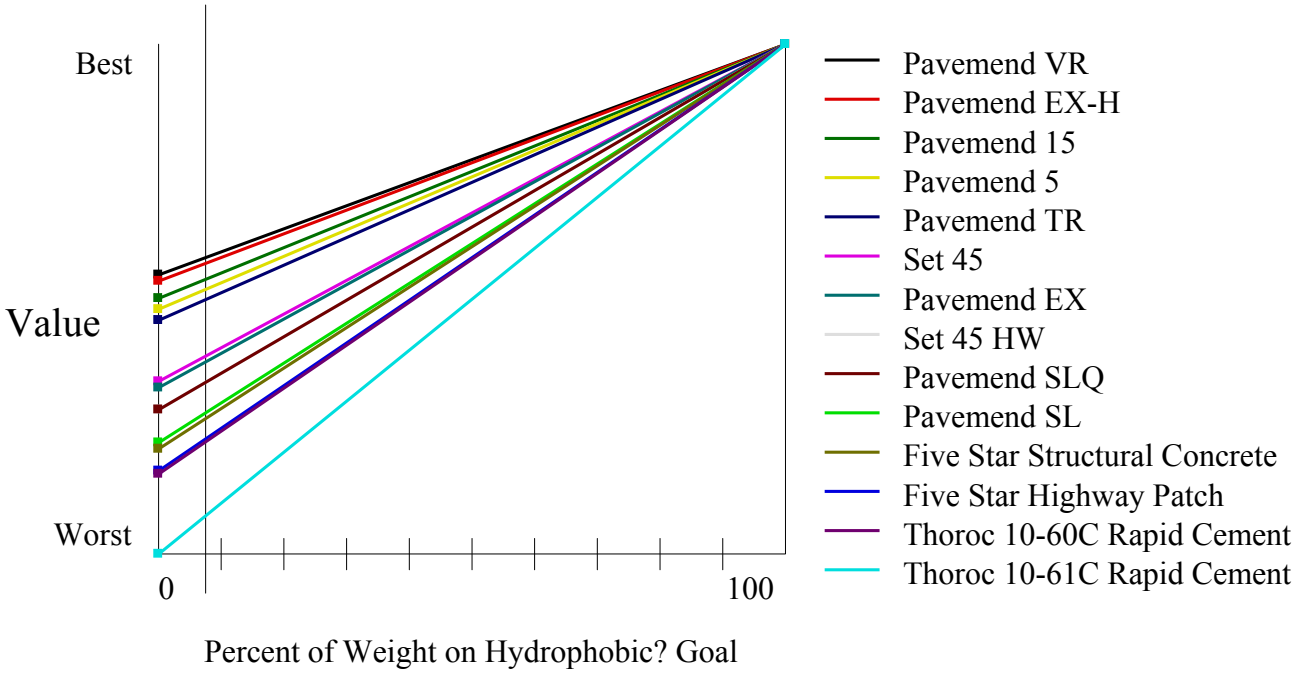
Percent of Weight on Modulus of Elasticity Goal



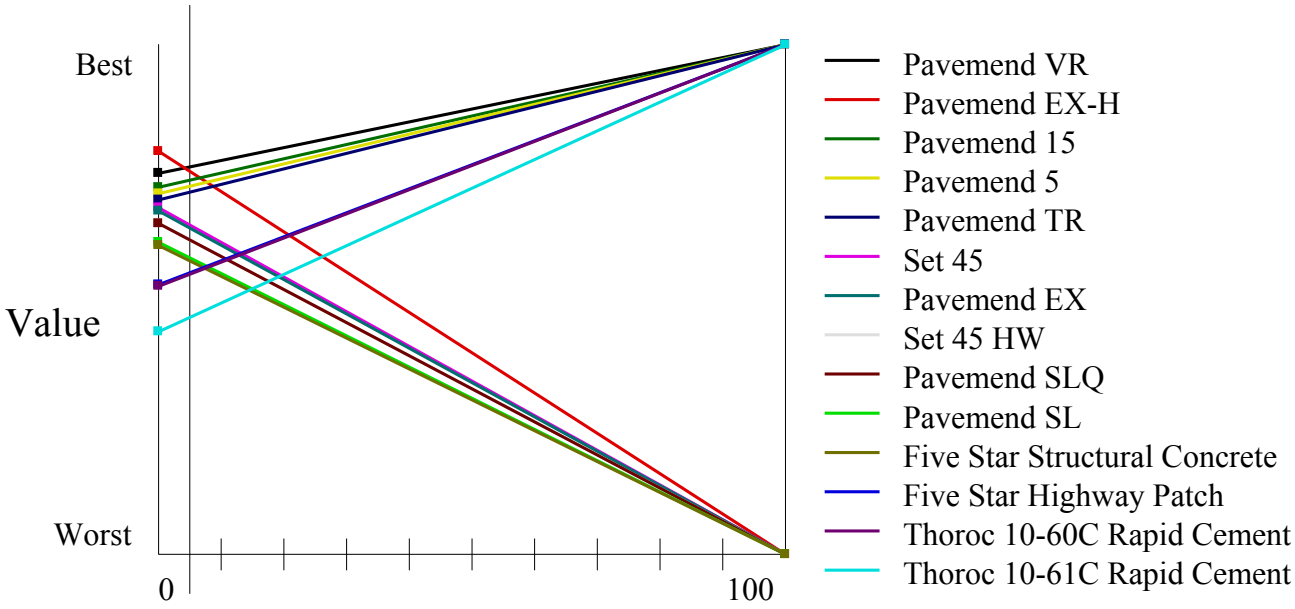
Percent of Weight on Restrained Drying Shrinkage Goal



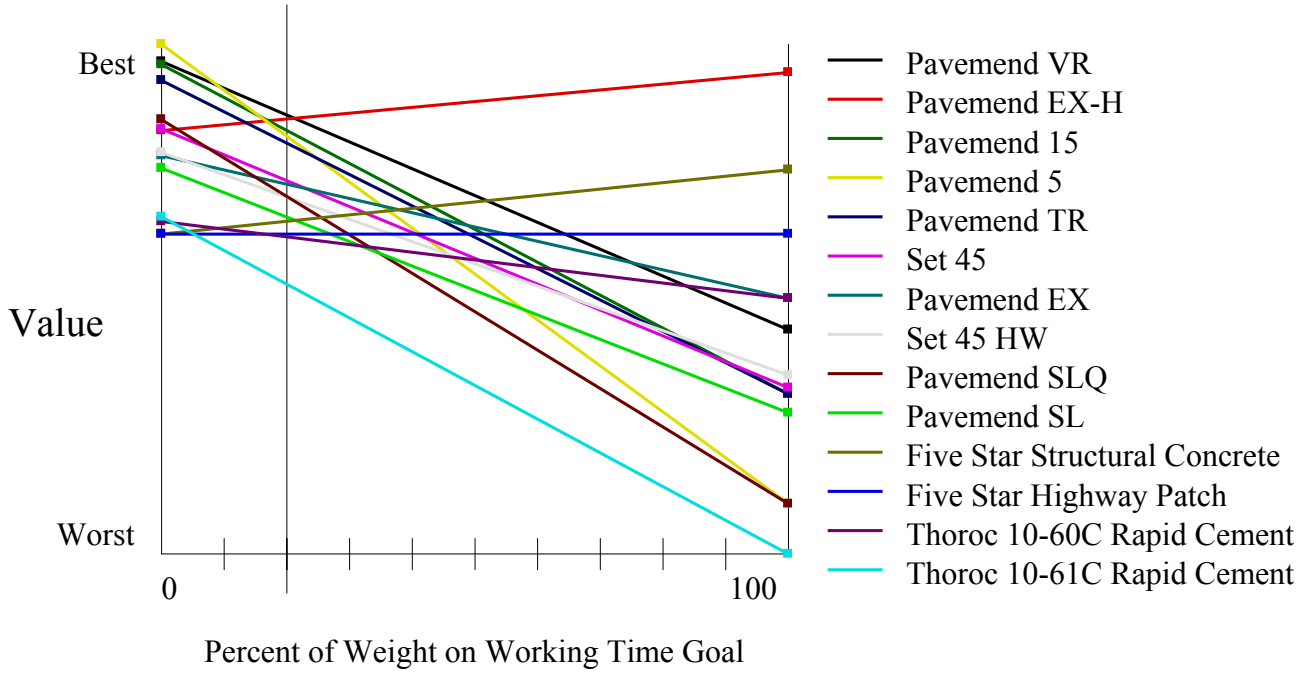
Percent of Weight on Thermal Expansion Goal



Percent of Weight on Hydrophobic? Goal



Percent of Weight on Aggregate/Lift Requirement Goal


Best
Value
Worst
0
100
Percent of Weight on Working Time Goal
Pavemend VR
Pavemend EX-H
Pavemend 15
Pavemend 5
Pavemend TR
Set 45
Pavemend EX
Set 45 HW
Pavemend SLQ
Pavemend SL
Five Star Structural Concrete
Five Star Highway Patch
Thoroc 10-60C Rapid Cement
Thoroc 10-61C Rapid Cement

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Vita

Captain Benjamin G. Speer graduated in May 1997 from Buchholz High School in Gainesville, Florida. He attended Embry-Riddle Aeronautical University in Daytona Beach, Florida, and graduated in May 2002 with a Bachelor of Science degree in Civil Engineering. He was commissioned through the Air Force Reserve Officer Training Corps, Detachment 157.

Captain Speer's first assignment was with the 30th Civil Engineer Squadron, Vandenberg Air Force Base, California. During this assignment, he served as an Environmental Flight Project Manager, as the squadron Unit Deployment Manager, and as an Operations Flight Maintenance Engineer. While at Vandenberg, he also deployed to Balad AB, Iraq, for 181 days as a RED HORSE Project OIC. Upon graduation, Captain Speer will separate from active duty, join the Air Force Reserves, and pursue a career in corporate management.

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14. ABSTRACT
Concrete spalls on airfield pavements generate foreign object debris (FOD) that is damaging to aircraft engines, and may damage landing gear by roughening of the pavement surface. Repairing spalled concrete on aging and deteriorating airfields is essential for its safe operational use. Picking the best repair material from many products on the commercial market is difficult. There is wide variation on material properties, and good performance on certain criteria is critical to constructing long lasting repairs. Since there is currently no procedure for Air Force decision–makers to select the best rigid-pavement repair material, a model was created using Value–Focused Thinking (VFT) to evaluate repair material alternatives. Fourteen products were compared against each other. Each was scored using fourteen evaluation measures that were identified as important to the repair material selection process. Pavemend EX-H was found to be the best choice for repairs conducted during conventional, steady-state operations. VFT was shown to be an effective methodology for objectively ranking repair products, while providing a systematic process that can be tailored for future circumstances.

15. SUBJECT TERMS
Decision Analysis, Value-Focused Thinking, VFT, Airfield, Concrete, Pavement, Spall, Repair

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